Robot-assisted rehabilitation of forearm and hand function after stroke

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Contents

Abstract

Stroke is the leading cause of adult disability in industrialized countries, affecting more than 10,000 people every year in Singapore. Brain damage most often results in strong impairment of the arm and hand motor functions in stroke survivors, which critically affects their activities of daily living (ADL) such as eating, manipulating objects, or writing. Therefore, physical rehabilitation is performed in hospital centers using intense arm and hand training, electrostimulation, or drug treatment. The results obtained with these therapies suggest that it is possible to partially restore hand function in stroke subjects and thus improve their quality of life. In particular, studies have shown that intense practice of repetitive movements can help improving the strength and functional use of the affected arm or hand. Robot-assisted rehabilitation is a recent approach to stroke therapy which promises to redefine current clinical strategies. Indeed, robotic devices can increase the intensity of therapy, objectively measure subjects' performance, progressively adapt assistance/resistance to the users' abilities, and propose motivating virtual reality exercises to perform therapy.

This thesis investigates robot-assisted rehabilitation after stroke, and presents the development of a new robotic device, the *Haptic Knob*, to train hand, wrist and forearm function. This robot is developed to exercise grasping and forearm pronation/supination, two fundamental tasks required in activities of daily living, and among those stroke survivors desire to recover most. The *Haptic Knob* considers the biomechanical constraints of the human hand, is adaptable to various levels of impairments, and can provide comfortable interaction. Further, the device is compact, safe and easy to use. Motivating game-like exercises are implemented, where subjects have to interact with the robot, actively perform movements or generate grasping force while receiving interactive visual, sensorimotor or psychological feedback. This approach facilitates concentration, motivates training and stimulates motor learning.

To validate the design and evaluate the feasibility of a therapy with the developed robot, a pilot study is conducted with chronic stroke subjects using the *Haptic Knob*, in combination with two other robotic devices specially developed for arm and finger rehabilitation. This study is one of the first to propose stroke survivors a personalized robot-assisted therapy at all levels of the arm, i.e. arm, hand and fingers. In a second step, a larger clinical study using the *Haptic Knob* only is conducted to evaluate the potential of this device as a rehabilitation tool. Results demonstrate the positive effects of robot-assisted therapy with the *Haptic Knob*, as participants to the studies show significant improvements in arm, wrist and hand motor function. Further the proposed therapy helps in decreasing impairments such as weakness and abnormal muscle tone observed in stroke subjects, leading to noticeable improvements in hand and wrist function that were maintained after the completion of the therapy. The results of this thesis provide new arguments in favor of robot-assisted stroke rehabilitation and contribute to improve our knowledge on motor recovery after stroke.

Keywords—robotics, hand and forearm function, stroke rehabilitation, motor recovery, Haptic Knob.

Version Abrégée

Les accidents vasculaires cérébraux (AVC) sont la principale cause d'infirmité chez les adultes de pays industrialisés, touchant plus de 10,000 personnes chaque année à Singapour. Les dommages cérébraux subis lors d'un AVC résultent le plus souvent en d'importants handicaps des fonctions motrices du bras et de la main, ce qui limite sévèrement les survivants d'un AVC dans leurs activités quotidiennes tel que se nourrir, manipuler des objets, ou encore écrire. La réadapatation post-AVC est pratiquée dans les hopitaux et centres spécialisés et est basée sur un entraînement intensif du bras et de la main, l'utilisation de stimulation musculaire électrique, ou d'injections intra-musculaires. Les résultats de ces thérapies suggèrent qu'il est possible pour les surviants d'un AVC de retrouver partiellement l'usage de leur main et donc d'améliorer grandement leur qualité de vie. En particulier, des études ont montré qu'une intense répétition de mouvements peut améliorer la force et l'utilisation fonctionelle du bras ou de la main affectée. La réadapatation assistée par robot est une nouvelle approche qui promet de redéfinir les stratégies actuelles pour le traitement des patients après AVC. En effet, les robots peuvent augmenter l'intensité de la thérapie, objectivement mesurer les performances des sujets, progressivement adapter l'assistance/résistance aux capacités de l'utilisateur, et profiter de la réalité virtuelle pour proposer une thérapie composée d'exercices motivants.

Cette thèse étudie la réadapatation assistée par robot après AVC et présente le développement d'une nouvelle plateforme robotique, le *Haptic Knob*, pour entraîner les fonctions de la main, du poignet et de l'avant-bras. Ce robot a été développé pour exercer la préhension ainsi que la pronation et la supination de l'avant-bras, deux tâches fondamentales nécessaires dans les activités quotidiennes, et parmi celles que les survivants d'AVC désirent le plus retrouver. Le *Haptic Knob* prend en compte les contraintes biomécaniques de la main, est adaptable à différents niveaux d'handicap, et est comfortable d'utilisation. De plus, le robot est compact, sûr et facile d'utilisation. Des exercices motivants présentés sous forme de jeux sont développés, où les sujets doivent intéragir avec le robot, générer activement un mouvement ou produire une force, tout en recevant un feedback visuel, sensorimoteur ou psychologique. Cette approche facilite la concentration, la motivation durant la thérapie et stimule l'apprentissage moteur.

Pour valider la conception et évaluer la faisabilité d'une thérapie avec le robot, une étude pilote est conduite avec des patients ayant subi un AVC, utilisant le *Haptic Knob* en combinaison avec deux autres robots spécialement développés pour la réadaptation du bras et des doigts. Cette étude est l'une des première à proposer une thérapie assistée par robot personalisée portant sur chaque segment du bras, i.e. le bras, la main et les doigts. Dans un deuxième temps, une plus large étude clinique utilisant uniquement le *Haptic Knob* est conduite pour évaluer son potentiel en tant qu'outil pour la réadaptation. Les résultats démontrent les effets positifs d'une thérapie assistée utilisant le *Haptic Knob*, les participants aux deux études montrant une amélioration significative de leur fonction motrice du bras, du poignet et de la main. De plus, la thérapie proposée permet de diminuer certains handicaps observés après un AVC tels que l'hypertonicité et la faiblesse musculaire, résultant en de remarquables améliorations des fonctions de la main et de l'avant-bras qui sont maintenues après la fin de la thérapie. Les résultats de cette thèse apportent de nouveaux arguments en faveur de la réadaptation après AVC assistée par robot et contribue à l'amélioration des connaissances en matière de restauration des fonctions motrices après AVC.

Mots-clés—robotique, fonction de la main et de l'avant-bras, réadaptation après accident vasculaire cérébral, restauration des fonctions motrices, Haptic Knob.

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Symbols

a	length of a parallelogram component of the *Haptic Knob* [cm]
a_1	coefficient for the calculation of S_1, a_1=15 [unitless]
a_2	coefficient for the calculation of S_1, a_2=0.5 [unitless]
A1−A9	subjects participating to the clinical study
b	length of a parallelogram component of the *Haptic Knob* [cm]
b_1	coefficient for the calculation of S_2, b_1=10 [unitless]
b_2	coefficient for the calculation of S_2, b_2=7.5 [unitless]
c	length of a parallelogram component of the *Haptic Knob* [cm]
d	length of one parallelogram rod [cm]
D	damping coefficient [N·s]
D_f	dynamic coefficient for friction compensation [N·s/cm]
f	number of degrees of freedom of a joint [unitless]
F_{comp}	friction compensation [N]
F_{ct}	thumb force during closing [N]
F_{cf}	fingers force during closing [N]
F_f	grasping force applied on the knob by the fingers [N]
F_g	grasping force [N]
F_p	perpendicular force [N]
F_{ot}	thumb force during opening [N]
F_{of}	fingers force during opening [N]
F_{rt}	thumb force during rest between opening and closing [N]
F_{rf}	fingers force during rest between opening and closing [N]
F_{static}	static friction force on the linear DOF [N]
F_t	grasping force applied on the knob by the thumb [N]
F_{test}	adapted resisted grasping force defined during preliminary session [N]
h	distance between endpoint and top of the parallelogram structure [cm]
I_{static}	current to compensate the static friction of the linear DOF [mA]
K	stiffness coefficient [N/m]

l	number of joints in the system [unitless]
m	endpoint of the parallelogram system (finger fixation) [cm]
M	total number of trials in a set [unitless]
M_1	motor for the linear opening of the *Haptic Knob* [unitless]
M_2	motor for the rotation of the *Haptic Knob* [unitless]
n_0	normalized number of zero crossing of the acceleration [1/s]
n_c	number of crossing in and out of target window [unitless]
n_{c_f}	number of crossing in and out of target force window for the finger force [unitless]
n_{c_t}	number of crossing in and out of target force window for the thumb force [unitless]
n_f	number of failed trials [unitless]
n_l	number of links in the system [unitless]
n_r	number of reaching movement failed [unitless]
N_{DOF}	number of DOF [unitless]
P1−P4	subjects participating to the pilot study
q_1	motor output for motor M_1 [counts]
q_2	motor output for motor M_2 [counts]
r_1	reduction ratio of motor M_1 [unitless]
r_2	reduction ratio of motor M_2 [unitless]
r_3	reduction ratio of the belt transmission [unitless]
r_f	radial aperture of the fingers parallelogram of the *Haptic Knob* [cm]
r_{out}	output parameter corresponding to the radial aperture of the *Haptic Knob* [cm]
rt	radial aperture of the thumb parallelogram of the *Haptic Knob* [cm]
R	radius of the pulley fixed on the shaft of motor M_1 [cm]
S_1	score of the opening/closing exercise [unitless]
S_2	score of the pronation/supination exercise [unitless]
t_{f_f}	time spent inside the target force window for the finger force [s]
t_{f_s}	time spent inside the target force window with both forces [s]
t_{f_t}	time spent inside the target force window for the thumb force [s]
t_m	time to perform the movement [s]
t_{out}	time spent outside the target window after reaching it for the first time [s]
t_s	setting time to reach the target force [s]
t_T	time to adjust the target after reaching it [s]
$v(t)$	velocity of movement [cm/s]
v_{max}	maximal velocity during movement [cm/s]
z_{in}	input parameter corresponding to the displacement of the linear module [cm]

Greek Letters

α	opening angle of the *Haptic Knob* [deg]

δ	shifting distance to change thumb movement velocity [cm]
ϵ_f	normalized absolute error between finger and thumb force [N/s]
ϵ_p	mean of absolute error between RPP and AP [cm]
ϕ	MCP extension angle [deg]
γ	angle between rotation axis of the thumb and the fingers [deg]
Γ_1	component to calculate the score S_2 [unitless]
Γ_2	component to calculate the score S_2 [unitless]
$\theta(t)$	angular position [deg]
θ_{in}	input parameter corresponding to the rotation of motor M2 [deg]
θ_{in}	output parameter corresponding to the rotation of the *Haptic Knob* [deg]
θ_T	target orientation [deg]
τ	pronation/supination torque applied by the robot [Nm]
τ_{test}	adapted resistive pronation/supination torque defined in preliminary session [Nm]
$\omega(t)$	angular velocity during movement [deg/s]
ω_{max}	maximal angular velocity during movement [deg/s]

Acronyms

ADL	Activities of Daily Living
AHA	American Heart Association
AP	Actual Position
ASA	American Stroke Association
AVC	Accident Vasculaire Cérébral
BCI	Brain Computer Interface
CG	Control Group
CIMT	Constraint Induced Movement Therapy
CMMII	Chedocke McMaster Impairment Inventory
CNS	Central Nervous System
COME	Control and Mechatronics
CPM	Continuous Passive Motion
DIP	Distal Interphalangeal
DOF	Degree Of Freedom
EPFL	Ecole Polytechnique Fédérale de Lausanne
EMG	Electromyography
ETHZ	Eidgenössische Technische Hochschule Zürich
FES	Functional Electrical Stimulation
FMA	Fugl-Meyer Assessment
fMRI	functional Magnetic Resonance Imaging
GUI	Graphical User Interface

ICORR	International Conference on Rehabilitation Robotics
IEEE	Institute of Electrical and Electronics Engineers
IRB	Institutional Review Board
IROS	Intelligent Robots and Systems
LED	Light-Emitting Diode
LSRO	Laboratoire de Systemes Robotiques
MAS	Motor Assessment Scale
MCP	Metacarpophalangeal
NHPT	Nine Hole Peg Test
NUS	National University of Singapore
OT	Occupational Therapy
PET	Positron-Emission Tomography
POM	Polyoxymethylene (DELRIN®)
PT	Physiotherapy
ROM	Range Of Motion
RPP	Reference Position Profile
SFU	Simon Fraser University
TMS	Transcranial Magnetic Stimulation
TTSH	Tan Tock Seng Hospital
USD	US Dollar
VR	Virtual Reality

Chapter 1

Introduction

1.1 Rehabilitation after Stroke

Stroke is the third leading cause of death, and the leading cause of adult long term disability in industrialized countries, affecting more than 10,000 people in Singapore every year, and more than 15 millions worldwide. About 70% of people survive the stroke, but most of them suffer from physical disabilities including hemiparesis, i.e. partial paralysis of one side of the body, sensory loss and impaired vocational capacity. Also, more than 50% of stroke survivors are unable to return to any type of working activity after the cerebral accident, and 33% require permanent care[1][2].

The cost of stroke in the United States for 2008 is estimated to be 65.5 billion USD, making stroke a major financial load to society. These costs include hospital/nursing home, physicians, drugs, equipment, and other indirect costs[3]. Rehabilitation after stroke is estimated to contribute to about 16% of the stroke costs, or 10.5 billion USD (Saxena et al., 2007; Taylor, 1997).

Rehabilitation can be defined as *the process of restoration of skills by a person who has*

[1]statistics form the Singapore National Stroke Association, 2005, http://www.snsa.org.sg

[2]statistics from the internet Stroke Center, 2008, http://www.strokecenter.org

[3]data form the 2008 report of the American Heart Association (AHA) and American Stroke Association (ASA); Heart Disease and Stroke Statistics 2008

had an illness or injury, so as to regain maximum self-sufficiency and function in a normal or as near as normal manner as possible[4]. Rehabilitation is essential after a stroke, and consists of one-on-one exercises with a physiotherapist or an occupational therapist, in a hospital or a specialized center. Exercises focus on muscle stretching and strengthening, manipulation of objects, standing and walking, in order to train functions necessary for independence and social integration. Although it is commonly admitted that rehabilitation should be intensive and should start as early as possible after the stroke, an optimal treatment for every patient has not yet been defined, and several different approaches are currently used in rehabilitation centers.

With longer life expectancy, it is expected that an increasing number of people will need rehabilitation services in the near future, which will increase healthcare costs. (Saxena et al., 2007; Kua, 1997). It is then necessary to investigate the efficiency of therapies, and develop new solutions in a way to optimize stroke rehabilitation by improving the quality of treatment with minimum cost.

1.2 Robotic Devices for Rehabilitation

Robot-assisted rehabilitation is one of the approaches that may redefine current clinical strategies (Hidler et al., 2005). A *robot* can be defined as a "programmable automation to augment human manipulation" (Mahoney, 1997), where programmable mean that a human can provide varying inputs which correspond to different states of the device. This definition might be too general, and in this thesis we will define a robot as a programmable electro-mechanical device capable of precisely interacting with humans by applying force or motion in a controlled and repeatable way.

The use of robots for medical application and interaction with humans was first investigated in the 1960's with the development of pioneering arm orthoses. However, it was in the 1990's, with the rapid development of robotics and new computer-based technologies, that

[4]definition from http://www.medterms.com, 2008

the potential of therapeutic robots became more and more evident, leading to major developments, in particular for stroke rehabilitation. As in industry, rehabilitation robots could be used to replace humans while performing tasks that require repeated effort.

An example is walking rehabilitation, which typically requires two therapists and considerable effort to support a patient and assist him or her to move the legs. A robot maintaining the patient and guiding the movement of the legs can reduce walking rehabilitation to a monitoring and analysis task for the therapists with the possibility of increased exercise for the patient. A similar approach could naturally be transferred to different functions and different parts of the body. However, the role of robots in rehabilitation is not to simply replace the therapist: rather robots will complement classical therapies.

1.3 Motivation and Challenges

The work in this thesis is motivated by the desire to improve the quality of therapy and understand the mechanisms of recovery after stroke. Currently the amount of therapy received by stroke survivors is not sufficient, as rehabilitation is often limited due to a lack of resources in hospitals and centers, i.e. the cost of therapists, material, and space. Robotic devices could increase the amount of therapy with affordable costs. Robots also offer additional advantages:

- robots can generate high forces to assist, resist, or guide subjects while performing movements. Moreover, forces can be delivered rapidly and smoothly enough to influence and study the neuromuscular control.
- forces applied by robotic devices can be accurately and systematically controlled to progressively adapt assistance/resistance given to the subject. Moreover, robots do not get tired and insure good repeatability of exercises.
- while classical rehabilitation is limited by subjective observation of therapists and patients, robotic devices are equipped with sensors that can precisely quantify the progress

achieved by patients. Further, treatments may be designed to adapt to a patient's level of impairment.

- robots offer the possibility to train in virtual environments using a variety of appropriate types of feedback, and game-like virtual reality exercises can motivate the subjects to train.

During the last decades, robotic rehabilitation after stroke focused on restoring arm function, yielding promising results that illustrate the potential of robots to complement traditional therapies and help in stroke rehabilitation (Prange et al., 2006; Kwakkel et al., 2008). However, proper arm function alone is not sufficient to perform most of activities of daily living (ADL), i.e. eating/drinking, writing/typing, personal hygiene. In fact hand function is fundamental to all these daily activities. These observations and the will to transfer the results of robotic arm rehabilitation to the hand motivated new developments focusing on upper extremities, i.e. wrist, hand and fingers.

Developing robotic devices dedicated to rehabilitation after stroke is a challenging task that covers a broad range of domains at the interface between engineering and medicine. Firstly, interacting with human subjects requires a high level of safety. Robots should be equipped with software and hardware limitations and emergency systems. Secondly, robots should also instill confidence. Fear of technological equipment is frequently observed, possibly even more in physically disabled people. This psychological factor is very important when the user of a rehabilitation robot has to place his or her limb on the device. An important challenge is thus to decrease the complexity of robotic systems so that they appear "friendly" while retaining their performance capability and safety. Third, robots to be used with stroke survivors require increased flexibility. They should accomodate the hand biomechanics of various subjects, so that they can adapt and compensate for user's impairment and offer a comfortable interaction.

1.4 Objectives

Despite the importance of hand function in ADL and rehabilitation, few robotic devices have been implemented and tested for rehabilitation of hand function after stroke. The main objective of our project is to conceive a new generation of robots for hand rehabilitation after stroke and assessment of hand function, based on current knowledge in rehabilitation robotics. The proposed systems will be implemented and tested with chronic stroke survivors to examine the potential benefits of this robot assisted therapy.

A second objective is to increase our knowledge of neuro-recovery following stroke by using information collected with the robotic devices, providing data to understand and assess hand impairment after stroke, and determine which types of therapy or exercises should be performed to provide optimal treatment.

More fundamentally, our project aims at helping stroke patients recover the use of their impaired hand and their independence, and offering therapy sessions to motivate them to exercise, as more time spend training will likely result in an improved motor function (Kwakkel et al., 2006).

1.5 Approach

1.5.1 Project Philosophy

A study was first performed on a population of 27 chronic stroke subjects to identify typical hand activities which were impaired in stroke survivors and which they desired to recover the most (Peterson, 2004). Results suggested that handwriting, typing, as well as operating knobs and buttons are activities that stroke survivors find difficult and would like to recover. This motivated us to develop robotic devices to train similar functional tasks. However, these hand activities are much more complex than arm movement; fine hand movements require precise control of the forearm, wrist and fingers and involve a large number of joints. Further, performing hand activities also requires the elbow and shoulder to support the weight and

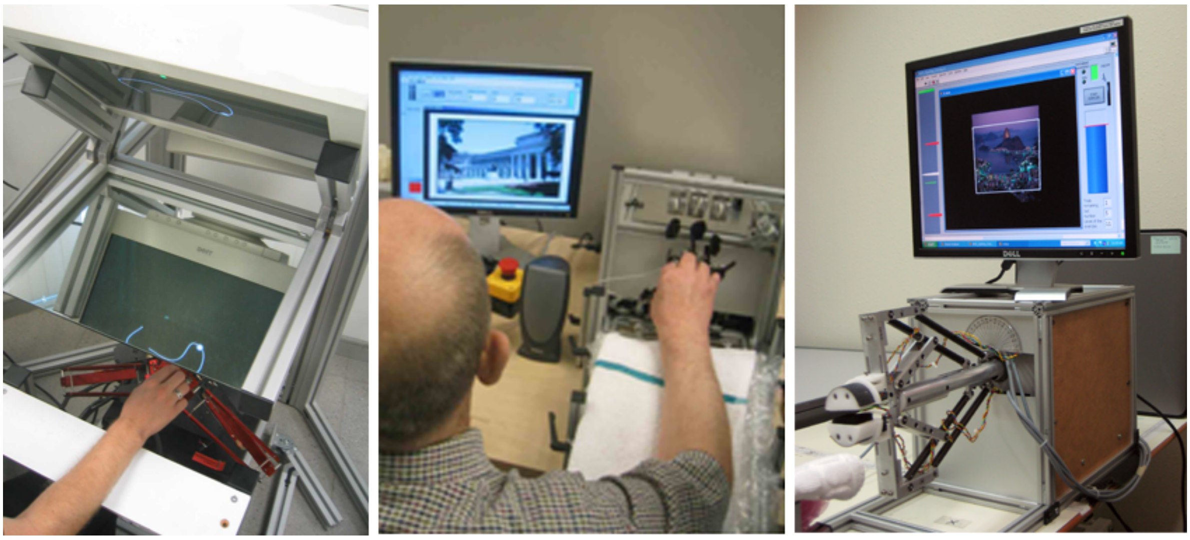

Figure 1.1: The three robotic systems designed, implemented and tested in our rehabilitation of hand function project. From left to right the *Delta Workstation*, the *HandCARE* and the *Hapitc Knob*.

position of the hand.

The approach used in this work is to decompose the complex tasks into a combination of simple subtasks to be trained individually, a technique commonly used for surgical training (Fei et al., 2004). Recent studies on rehabilitation of arm function in stroke patients reported no better results than when complex tasks were trained directly (Krebs et al., 2008); however it presents the advantage of simplifying both the robot design and the implementation of exercises. For example, the task of operating a door knob can be decomposed into a series of subtasks (i) reaching for the knob, (ii) grasping the knob, (iii) turning the knob, and (iv) releasing the knob. These subtasks can be trained separately with dedicated interfaces and exercises that were developed in our project (Fig. 1.1).

One of the main goal behind the development of robotic devices is to be able to perform rehabilitation at home or in decentralized rehabilitation centers. Having stroke patients training in the context of their daily activities, without burden and costs of transportation and with only minimal (or remote) supervision from therapist may be the optimal solution to increase the amount of therapy without increasing the costs. The robots we have developed tend to realize this goal and are thus designed to be safe when used by the patient alone, compact, "plug and play" on a regular computer, simple to use, adaptable to patient's impairment, and relatively inexpensive for patient or rehabilitation centers to buy or rent.

1.5.2 Thesis Contributions

The first phase of this project consisted in the identification of the specific tasks to train, and the design of three robotic devices to provide upper limb rehabilitation at different levels, i.e. arm, hand and fingers. Several experiments with healthy and post-stroke subjects were performed to determine specifications for these devices, and to develop rehabilitation tools that were efficient, safe and comfortable to use. The design of three robotic devices was performed in collaboration with Ludovic Dovat at the National University of Singapore (NUS) (Dovat, 2009), and with the contribution of partners at the Ecole Polytechnique Fédérale de Lausanne (EPFL), Simon Fraser University (SFU), Imperial College London, and NUS. My main contribution to this work was focused on the design, implementation and evaluation of one of the robot, the *Haptic Knob*, to train hand, wrist and forearm function.

In a second phase, robotic devices were constructed with the objective of having flexible, compact and safe devices. Different strategies were investigated to implement task-oriented exercises inspired from typical ADL, enhancing active participation of subjects. Exercises were presented as virtual games with personalized levels of difficulty and various feedback techniques such as visual, sensory and audio feedback, to increase concentration and motivation for training.

The third phase of this project consisted of a pilot study with four chronic stroke subjects over a period of eight weeks, using the *Haptic Knob* and the other two devices. The objective of this study was to demonstrate the feasibility of a therapy program involving the developed robots, and evaluate the benefits of such program.

Based on the results of the pilot study, a larger clinical study involving nine stroke subjects training with only one robot, the *Haptic Knob*, was conducted to determine the potential of this robot as a rehabilitation tool.

This work has so far resulted in two journal papers, eleven conference publications and two patents, as listed below. This work received the "Best Application Paper Award" at the IEEE International Conference on Intelligent Robots and Systems (IROS) 2006, the "First Runner Up" position in the Andrew Fraser Prize 2008, and the best presentation award at the IEEE International Conference on Robotic Rehabilitation (ICORR) 2009. It also resulted in the organization of a special session at the IEEE International Conference on Rehabilitation Robotics (ICORR) 2007.

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1.6 Thesis Outline

Chapter 2 introduces stroke and the mechanisms underlying functional recovery. Physical impairments resulting from stroke, and traditional rehabilitation therapies to restore motor and sensory functions are listed. Existing robotic devices for stroke rehabilitation are presented and discussed, with a specific interest for devices dedicated to hand rehabilitation.

Chapter 3 presents the design and development of three robotic devices for stroke rehabilitation, the *Delta Workstation*, the *HandCARE*, and the *Haptic Knob*. The constraints for the mechanical design, the investigated solutions, as well as the development, the implementation and the evaluation of the *Haptic Knob* are presented in this Chapter.

Chapter 4 describes the approach used for the development of exercises for stroke rehabilitation, in order to take advantage of the features of the robots while keeping the exercises simple and motivating for subjects.

Chapter 5 presents the results of a pilot study with four stroke survivors that was performed at SFU (Vancouver, Canada) using the three developed robots. The exercises with the *Haptic Knob* are described and the outcome of the robot-assisted rehabilitation therapy is discussed for each subjects.

Results of a larger clinical study involving nine stroke subjects training with the *Haptic Knob* are presented and discussed in Chapter 6. This study was conducted at Tan Tock Seng Hospital (TTSH) Rehabilitation Center (Singapore), with the collaboration of physicians, physiotherapists and occupational therapists.

Finally, Chapter 7 summarizes the contributions of this work and discusses the future of robot-assisted rehabilitation and in particular for the *Haptic Knob*.

Chapter 2

Stroke and Rehabilitation Strategies

This chapter introduces the mechanisms of recovery after stroke that are the foundation of rehabilitation theories. The common impairments observed in stroke survivors are described to identify the constraints for the design of robotic devices. Finally, rehabilitation techniques proposed for stroke patients are presented to illustrate classical and new approaches to stroke rehabilitation, and the potential of robot-assisted devices.

2.1 Stroke and recovery

Stroke is the result of diseases involving the blood vessels, affecting people of different ages, genders, or ethnic groups. Stroke is caused *(i)* by the obstruction of a blood vessel inside the brain, referred to as occlusive or ischemic stroke, or *(ii)* by local bleeding inside the brain, referred to as hemorrhagic stroke (Fig. 2.1). In all cases, the blood flow to specific areas of the brain is interrupted depriving brain cells of their oxygen and glucose supply. If these conditions are prolonged, neurons and other cellular elements die, causing significant damage to the brain (Kandel et al., 2000).

Neuroplasticity, or *brain plasticity*, is the brain's ability to reorganize and create new neural connections throughout life. This phenomenon is responsible for our capacity to learn new information, improve and consolidate functions that are already acquired. In addition to brain

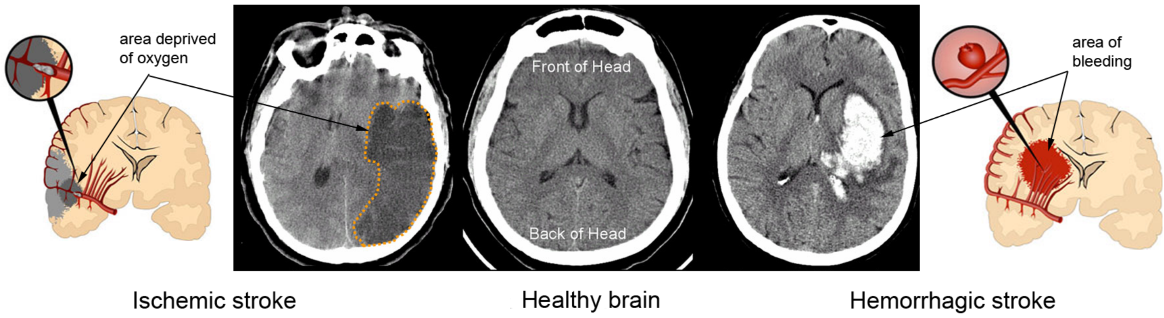

Figure 2.1: Types of stroke; scheme and brain scan of an ischemic stroke caused by the obstruction of a blood vessel inside the brain (left). Scheme and brain scan of a hemorrhagic stroke due to the bursting of a blood vessel causing internal bleeding (right) (adapted from http://stroke.ucsf.edu and http://uwmedicine.washington.edu).

changes attributed to learning, the nervous system can also compensate in case of injury or disease; unimpaired neurons from different areas of the brain can form a new network that can potentially take over lost function.

The recent development of brain imaging techniques such as Positron-Emission Tomography (PET) or functional Magnetic Resonance Imaging (fMRI), and diagnosis techniques such as Transcranial Magnetic Stimulation (TMS), brought new tools to investigate and validate the hypothesis of brain plasticity (Feydy et al., 2002). Neuroplasticity is spontaneous in the first few months following a stroke, due to a local reorganization of the brain to compensate for the new weakness. Several studies on post-stroke subjects using TMS have shown that intensive training of the impaired limb lead to changes in areas of brain activity that are correlated with recovery (Leipert et al., 2001). Typically, Sawaki et al. observed that after receiving intensive hand therapy for several weeks, with active participation of the impaired limb, the area of the brain corresponding to the hand expanded, suggesting that brain cells previously involved in the other functions can be retrained to move the hand (Sawaki et al., 2008). These results suggest that intensive rehabilitation therapy for people with stroke actually stimulates brain plasticity and promotes recovery.

Figure 2.2: Hand impairment in two post-stroke subjects that participated to our clinical studies. The main characteristics observed are weakness of wrist and finger extensors muscles associated with high muscle tone and abnormal synergies in flexor muscles.

2.2 Hemiparesis and impairments following stroke

Stroke generally affects motor functions of the lower and upper limb, decreasing the ability to walk or use the arm and hand. *Hemiparesis*, a paralysis or weakness of one side of the body, is the most common outcome of stroke, leading to movement deficits in the limb opposite to the side of the stroke. The main characteristics observed in hemiparetic patients are: weakness of specific muscles; abnormal muscle tone; abnormal postural adjustments; lack of mobility; incorrect timing of components within a pattern; abnormal movement synergies and loss of interjoint coordination, and loss of sensation (Cirstea and Levin, 2000).

The hand, because of its complexity in terms of number of muscles and joints to control is likely to be impaired after a stroke, and to be affected by the previously listed symptoms, limiting patient's autonomy in ADL and potentially resulting in permanent disabilities (Fig. 2.2).

2.2.1 Muscle weakness

Muscle weakness is often considered as the main impairment resulting from a stroke (Kamper et al., 2006). It is generally caused by damage in corticospinal pathways at the level of the brain. The efferent input to the muscles is decreased, and activation of the muscles is more difficult (Chae et al., 2002). Additional muscle weakness may result from a non-use of the impaired limb. Muscle weakness is mainly observed in finger and wrist extensors, impeding movements and activities requiring hand opening.

2.2.2 Abnormal muscle tone

Stroke produces an initial paresis, which is gradually replaced by hypertonicity, or *spasticity*, in muscles flexing the fingers, leading to a flexed resting hand posture (Kamper et al., 2006). Kamper et al. studied the deficit in motor control of finger extension in chronic stroke patients. They illustrated an excessive inappropriate coactivation of finger flexor and extensor muscles, leading to the impossibility to produce extension torque at the metacarpophalangeal (MCP) joint, and even in the generation of flexion torque instead of the desired extension torque (Kamper and Rymer, 2001). Similar results have been observed at the level of the wrist joint of chronic stroke patients (Hammond et al., 1988). One of the hypotheses to explain the excessive contraction of specific muscles is a change in the level of excitability of alpha motorneurons (Chae et al., 2002). A reduction in the inhibition of finger flexor by extensor afferents can also be a possible explanation to this phenomenon (Kamper and Rymer, 2001).

2.2.3 Lack of mobility

Due to flexor muscle impairment, the workspace of the hand and fingers is dramatically reduced. Cruz et al. studied movement and force generation of the index finger in chronic stroke patients (Cruz et al., 2005). They observed a direct relation between the level of impairment and the force generating capacities, severely impaired patient being weaker than healthy control subjects. The workspace of the finger was reduced to less than 10% of healthy subjects' workspace for the most impaired patients.

2.2.4 Abnormal movement synergies and loss of interjoint coordination

Another major problem following stroke is the incoordination between the different joints due to abnormal muscles synergies. Typically, all flexor muscles in the arm react in a synergistic pattern that is superimposed on normal muscle activity. The use of strong flexors, such as the biceps, results in uncontrolled flexion of the wrist and closing of the hand. In the case of the fingers it severely decreases the range of motion but also finger independence (Lang and Schieber, 2004; Schieber and Santello, 2004; Raghavan et al., 2006), impeding activities such as typing. Cirstea et al. studied reaching movement with the arm in chronic stroke patients, and observed a decreased speed, a greater segmentation and a decrease in precision of the movement (Cirstea and Levin, 2000). The development of compensatory strategies to perform the desired movements is also observed, especially movement of the trunk to compensate for reduced shoulder or elbow movement.

2.2.5 Lack of sensitivity

After stroke, loss of sensation in the hand and fingers is frequently observed. Somatosensory loss is manifested by delayed perception, uncertainty of responses, changes in sensory threshold, fatigue, increase or decrease in time for sensory adaptation to occur and altered nature of the sensation (Hunter and Crome, 2002). In terms of function, proprioception, vibratory sense, light touch ability and pinprick sensation are most affected by stroke. This results in difficulties in detecting texture, shape and size of objects.

These impairments are often linked together, severely limiting subject's ability to perform ADL. Additionally, stroke not only affects motor function but can have many other dramatic consequences; speaking, comprehension, memory and concentration capabilities are often affected.

2.3 Hospital Care System

Within hours after a stroke, survivors are admitted into a hospital where the long process of rehabilitation starts. This section details the different steps and options during stroke rehabilitation, and identifies the strengths and weaknesses of conventional rehabilitation, by describing the therapies proposed at Tan Tock Seng Hospital (TTSH) in Singapore.

TTSH is the second largest hospital in Singapore, with the largest and most established rehabilitation facility dedicated to the treatment of patients with neurological diseases such as stroke, or traumatic brain injuries. The objectives of neurorehabilitation at TTSH are to improve functional outcome in areas of mobility, upper limb use and performance of ADL, and to improve speech and swallowing function, continence and cognitive functioning. Other important areas include mood and psychological issues, sexuality and sexual function and coping with disability.

2.3.1 Stages of the stroke

Directly after a stroke, patients are admitted into the hospital where their medical condition is monitored. The first few days are marked by spontaneous brain reorganization. Patients are in shock; the body and the central nervous system (CNS) are recovering from the stroke, giving priority to reestablishing vital functions i.e. stabilizing the heart rhythm and other internal functions. During this first stage, referred to as the *acute stage*, patients remain in bed, receive medical attention and drug treatment, and undergo diagnosis.

Patients start physiotherapy as soon as the heart rhythm is stabilized, to benefit from maximal neuroplasticity. This stage is referred to as the *subacute stage* of the stroke, and may start from a few days to few weeks after the stroke. Patients remain inside the hospital i.e. *inpatients*, and receive daily sessions of physiotherapy at a rehabilitation center. The primary goal of early physiotherapy is to train standing, balance, then walking. Progressively, sessions of occupational therapy are integrated into the rehabilitation program to train functions used in ADL, typically arm and hand function. Patients are systematically assessed with standardized clinical tests every week to keep track of the progress.

Once patients can stand and walk with the help of caregivers or assistive devices, patients are discharged from the hospital and can go back to their home, i.e. *outpatients*. This generally happens within weeks and up to 3 months after the stroke (Venketasubramanian and Yin, 2000). During that time patients come 2 to 3 times per week to the rehabilitation center during a period from 3 to 6 months, to receive personalized therapy sessions adapted to their needs. At home, additional treatment can be provided by independent caregivers.

After 6 to 9 months post stroke spontaneous recovery stops and neuroplasticity becomes minimal. This is referred to as the *chronic stage* of the stroke. In the chronic stage, the medical condition is stable as patients reach a plateau where further improvement is limited. Patients may then continue to regularly come to the rehabilitation center for therapy, or seek help in stroke recovery clubs and in the stroke community.

Figure 2.3 summarizes the time frame and different steps of the rehabilitation process after stroke.

2.3.2 Neurorehabilitation programs

Physiotherapy (PT):

Physiotherapy programs consist of exercises with stretching and movement repetitions to strengthen muscles, decrease tone and help relearn how to use impaired limbs, typically how to move the legs and position the body weight for walking. Different approaches are commonly used: the *Bobath approach*, widely used in European countries, aims at inhibiting spasticity and synergies, and to encourage voluntary movement and intensive use of the affected limb in all activities (Bobath, 1977). The *Brunnstrom approach* encourages the development of flexor and extensor synergies during early recovery, and later aims at transforming the synergistic

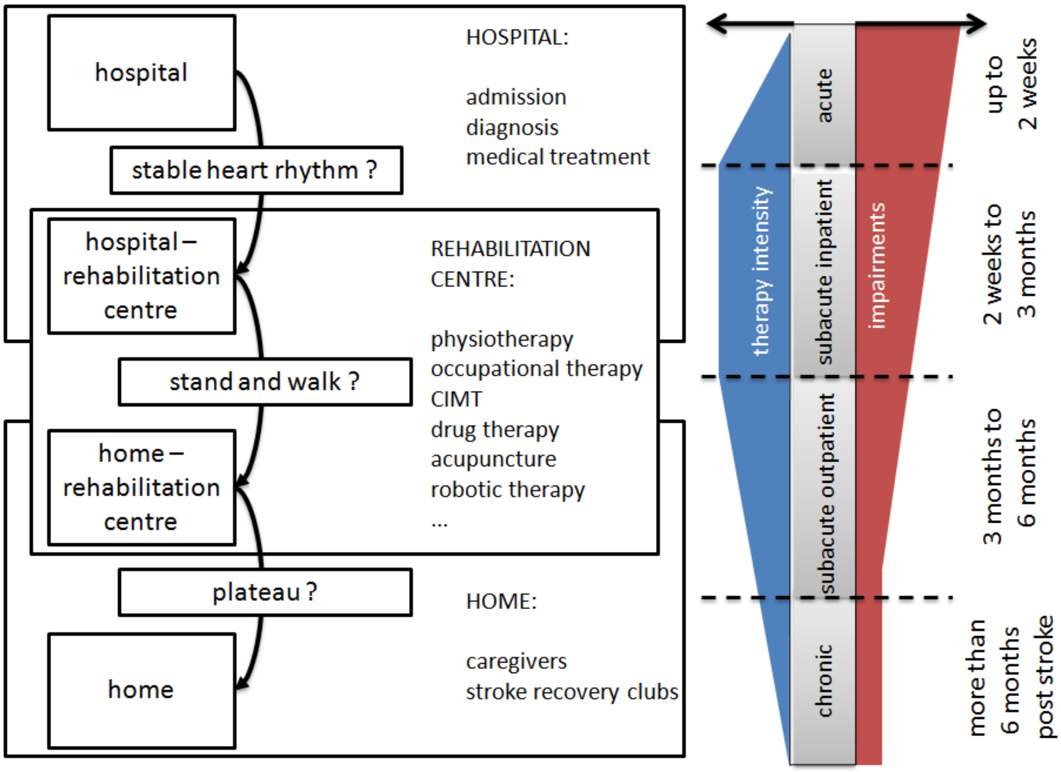

Figure 2.3: Flowchart with the different steps of stroke rehabilitation at the hospital, rehabilitation centre and home. On the right, diagrams illustrating the intensity of rehabilitation therapy (left) and the theoretical evolution of the impairments (right) during the therapy.

muscle activation into voluntary activation through intensive training.

Occupational therapy (OT):

Occupational therapy aims at training functions used in ADL, by intensively practicing with familiar objects, or in domestic environment. Figure 2.4 A and B illustrate typical simple elastic tools that are used to train hand and fingers. OT also aims at teaching patients how to live with a disability, and how to accommodate their environment to their disability.

None of these approaches has been proven to be much superior to the others, thus the most common clinical practice is to incorporate components of all therapy methods, as a function of the needs of the patient (Luke et al., 2004). In addition, during the last decades,

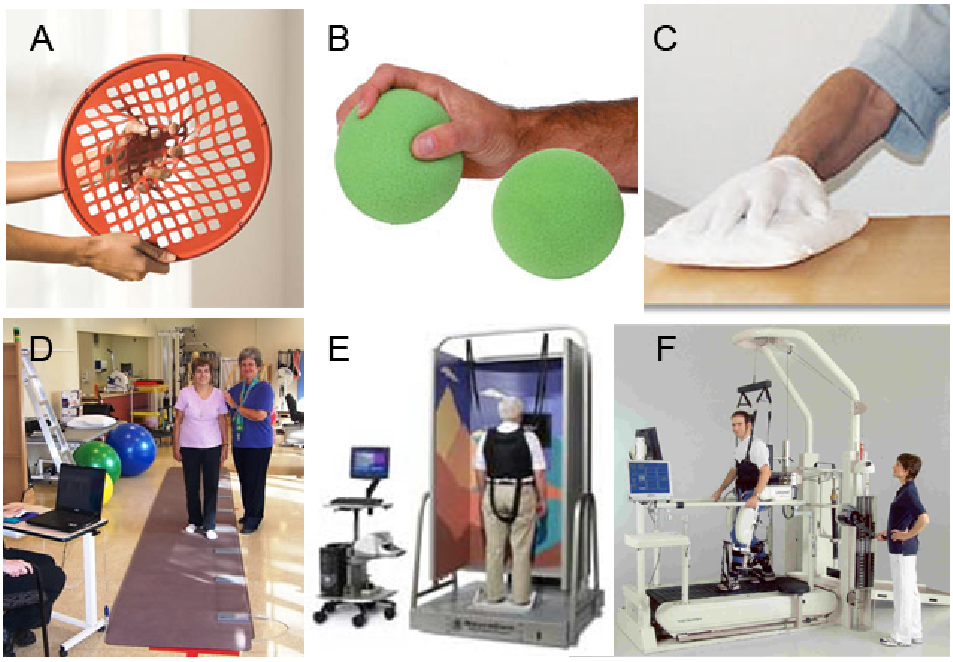

Figure 2.4: Tools used in rehabilitation centers for therapy and assessments. A-B: passive elastic devices used in OT, C: CIMT, where the use of the unimpaired hand is restricted, D: GaitRite® assessment of gait parameters, E: Balance Master® to train and assess balance, F: Lokomat® robot to exercise walking.

new therapy programs focusing on specific functions, or involving new technologies, have been introduced to rehabilitation centers to complement PT and OT. For example, the following neurorehabilitation programs for upper and lower limbs are proposed at TTSH:

- Constraint-Induced Movement Therapy (CIMT): CIMT is a treatment consisting of a 2-week long program designed to improve hemiplegic arm function and help patients overcome learned non-use of the impaired limb. This technique involves restraint of the unimpaired limb (Fig. 2.4 C), in combination with a large number of repetitions of task-specific training of the affected limb. Several studies have demonstrated the potential of CIMT to improve upper limb function following stroke compared to alternative and/or no treatment (Page et al., 2004; Wolf et al., 2006). However, one important concern of this technique is the length of time patients are required to spend in therapy; the arm is restrained during 90% of waking time during 2 weeks, which may be too strenuous for patients. Additionally, CIMT cannot be applied to severely impaired patients, as they should already be able to perform fundamental ADL, for example patients should be able to hold a walking stick, or eat with their impaired hand. Although potentially effective, CIMT is thus not feasible for a majority of patients (Hakkennes and Keating, 2005).

- Botulinum toxin injection: the treatment consists in injection of Botulinum toxin (Botox®) in hand or arm muscles to relax the contracted muscles in a way to decrease spasticity (Slawek et al., 2005; Brashear et al., 2002). However, Botox® injections have to be regularly repeated every 2 to 3 months in order to maintain improvement and is thus not a long term solution. Additionally, if injections decrease muscle tone, they have limited to no effect on other impairments such as muscle weakness. Ideally, drug treatment should be a complement to classical therapy; the weakening of treated muscles offering an opportunity to strengthening the antagonist muscles and thereby it is possible to restore some of the balance between the two, and potentially lead to greater improvements (Ward, 2008).

- Acupuncture: this treatment consists in insertion and manipulation of fine needles into specific points of the body with the aim of relieving pain and other therapeutic reasons. However, efficiency of acupuncture for stroke rehabilitation is still controversial.

- Functional Electrical Stimulation (FES): FES consists in the artificial electrical stimulation of a muscle that has diminished nervous control, to produce a functionally useful movement. In stroke rehabilitation, FES is used to help subjects optimize functional performance, typically by stimulating hand muscles to grasp and hold objects.

- Robotic assessments: gait parameters such as velocity, stride length, gait symmetry and foot pressure mapping can be measured using commercially available tools, such as GAITRite®[1], a mat with embedded sensors (Fig. 2.4D). Similarly, commercial systems

[1] http://www.gaitrite.com

such as the Balance Master® can assess and train balance by having patients stand on an orientable robotic plate. The device can move in response to patient movement to maintain balance, or in an unpredictable way for patients to adapt their posture (Fig. 2.4E). These types of assessment tools provide physiotherapists with objective measures allowing them to customize training for patients to improve walking.

- Robotic rehabilitation: few commercially available robotic devices are integrated in rehabilitation centers to provide robot-assisted therapy. Typically, walking exercises are performed on a robotic gait orthosis, the Lokomat®[2]. The robot can compensate for an individual's body weight, and automate walking therapy on a treadmill system. This reduces the fatigue and work of ambulation for dependent patients and enables them to walk for longer periods of time (Fig. 2.4F).

2.4 Robots for rehabilitation

During the last decades, several robotic devices for rehabilitation have been developed with the objective to improve the quality of treatment provided to stroke survivors, taking advantage of robot properties. Indeed, robotic devices can complement labor-intensive interactions between therapist and stroke subjects, as they can provide high-intensity, repetitive, adaptable, and task-specific treatment of the impaired limb. Moreover, robots can use virtual reality (VR) environments, or other types of feedback, to offer challenging and motivating training. Robots also provide objective and reliable means of monitoring subjects' progress (Prange et al., 2006). Several robots have been developed for arm and, more recently, for hand rehabilitation (Fasoli et al., 2004; Krebs et al., 2008; Lum et al., 2002; Adamovich et al., 2005; Takahashi et al., 2008). The results suggest that the robot-assisted treatment may achieve increased gain relative to the traditional therapy. Figure 2.5 illustrates some of the existing robotic devices for hand rehabilitation.

[2]http://www.hocoma.ch

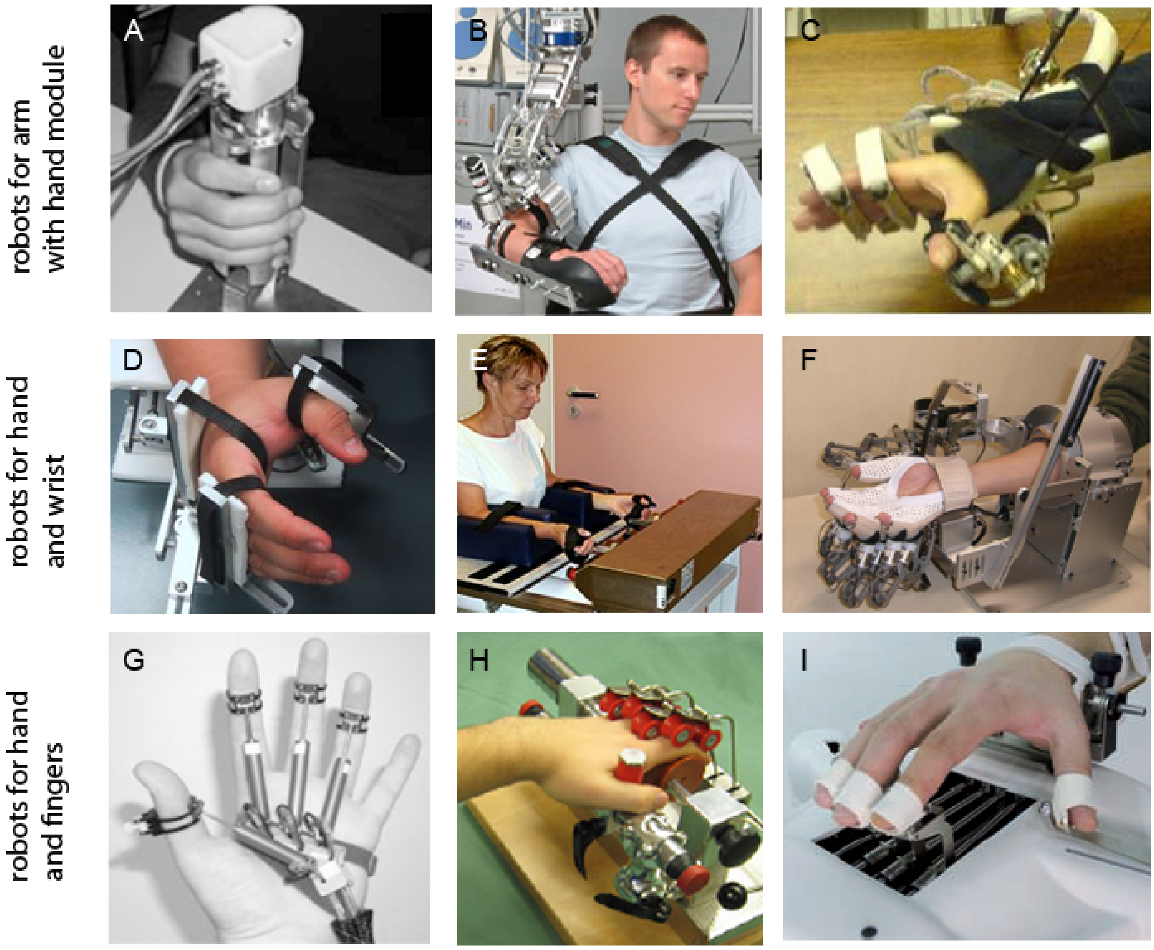

Figure 2.5: Robotic devices for hand rehabilitation. Arm robots with extension module to train hand function: the Hand Robot Alpha-Prototype II on the MIT-MANUS (Masia et al., 2007) (A), the ARMin (Nef et al., 2006) (B) and the GENTLE/G system (Loureiro and Harwin, 2007) (C). Robots dedicated to wrist and hand rehabilitation: the HWARD (Takahashi et al., 2005) (D), the BiManuTrack (Hesse et al., 2003) (E) and the Gifu haptic Interface (Kawasaki et al., 2007) (F). Robots dedicated to hand and fingers rehabilitation: the Rutgers Master II (Bouzit et al., 2002) (G), the Finger Trainer (Hesse et al., 2008) (H) and the Amadeo system (Kollreider et al., 2007) (I).

2.4.1 Robots dedicated to arm and hand rehabilitation

Several groups which have developed robot-assisted arm rehabilitation have added a hand module with the objective of creating a robotic device capable of training the entire arm and hand function.

Hogan et al. have developed the Hand Robot Alpha-Prototype II, an extension for their arm rehabilitation device, the MIT-MANUS. The MIT-MANUS is a commercially available[3] planar 2 DOF robot developed to train arm and shoulder and simulate arm reaching movements (Hogan et al., 1995). The hand module is a handle fixed at the extremity of the robot that can provide high force to train grasping, and assist hand opening by progressively changing its diameter (Masia et al., 2006, 2007). Nevertheless, this solution may be limited by a small ROM and the inability to train hand opening from a closed hand.

Riener et al. have developed the ARMin, a rehabilitation robot comprising 4 active DOF allowing shoulder and elbow movement. The distal part of the robot is characterized by an exoskeletal structure, with the patient's arm placed inside an orthotic shell (Riener et al., 2006). A 2 DOF hand module has been developed to train forearm pronation/supination and wrist flexion/extension. However, this device does not offer training for grasping or finger movement (Nef et al., 2006).

Loureiro et al. have developed the GENTLE/G system, composed of a wrist-orthosis connected to a HapticMaster robot providing 3 active DOF that can train 3D reaching movements, with the possibility of compensating for the weight of the arm. The wrist orthosis has 3 passive DOF to allow comfortable positioning during movements. A 3 DOF gripper has been mounted on the structure to train reach to grasp activities, and allow for practicing key grips, power and pinch grasps (Loureiro and Harwin, 2007).

2.4.2 Robots dedicated to wrist and hand rehabilitation

In contrast to the previously described robots, several devices have been developed to focus on training wrist and hand functions. This resulted in less complex and more compact robotic devices.

Takahashi et al. developed HWARD, a pneumatically actuated 3 DOF robot to train grasping and releasing of objects. The robot allows flexion/extension of the four fingers as a single unit, the thumb, and wrist. The device contacts the subject along the dorsal side of

[3]InMotion2 from Interactive Motion Technologies, inc., http://www.interactive-motion.com

the fingers, hand, and thumb. This design leaves the region of the open hand unobstructed, permitting manipulation of real objects (Takahashi et al., 2005).

Hesse et al. have developed the BiManuTrack, a commercialized[4] 1 DOF device that can separately train wrist flexion/extension and forearm pronation/supination (Hesse et al., 2003). The system is composed of two handles actuated with a master-slave system based on the motion of the healthy limb. This system allows forearm and wrist movement but cannot train grasping and fine finger motion.

Kawasaki et al. designed the Gifu Haptic Interface, an exoskeleton with 18 active DOF allowing individual movement of different finger joints to exercise finger flexion/extension and adduction/abduction, wrist flexion/extension and forearm pronation/supination (Kawasaki et al., 2004, 2007). This setup is based on a master-slave system; the motion of the healthy hand is recorded with a data glove, and the robot produces an equivalent motion for the affected hand. Although almost any hand movements can be replicated, the complexity of the system and the difficulty to adapt the exoskeleton to different hand sizes may limit the use of such a device.

2.4.3 Robots dedicated to hand and fingers rehabilitation

Finger movement and independence are fundamental in ADL. This motivated research groups to develop robots capable of training individual fingers movements.

Pioneering work in robotic assisted rehabilitation of hand function was performed by Burdea et al. with the Rutgers Master II (Bouzit et al., 2002), a dedicated robotic glove with pneumatic actuators fixed to the palm to actuate each finger except the little finger, individually or together. However, the ROM of the robot is limited because of the position of pistons in the palm of the hand.

Hesse et al. recently developed an electromechanical Finger Trainer to move every finger except the thumb through a physiological range of movement. The system is composed of

[4] http://www.reha-stim.de

plastic rolls fixed eccentrically to the powered axle of the device, forming a camshaft (Hesse et al., 2008). The goal of this device is to passively train finger extension for subjects with paralysis or high spasticity.

Kollreider et al. have developed Amadeo®[5], a robotic device capable of moving each finger in flexion/extension in an individual and natural way. One actuated DOF linearly moves each fingertip in a horizontal plane while a custom built sledge with 2 passive DOF allows natural orientation of the fingertip during movement (Kollreider et al., 2007). However, this system may not be well adapted to subjects with finger spasticity.

2.4.4 HandCPM

Several commercially available robots propose Continuous Passive Motion (CPM) of the hand, to prevent the development of stiffness in the joints. Hand CPM technology includes devices of varying portability that can be attached to the hand and wrist by means of braces and that are connected to the fingertips. Most devices work by passively moving the tips of the fingers, pulling them up to open the hand, and then reversing the movement. However these devices are not well adapted for patients with spasticity, they can not train active finger movements, and most Hand CPM devices do not include training for the thumb. Figure 2.6 presents several commercialized CPM devices.

Figure 2.6: Examples of commercial Hand CPM devices: the Meastra Hand and Wrist CPM, the Kinetec Maestra Portable Hand CPM and the DigiGlide (adapted from http://www.medsourceusa.com, http://www.metmedicalcpm.com and http://www.omnimotion.net).

[5] http://www.tyromotion.com

2.4.5 Synthesis

Table 2.1 summarizes the properties of the principal existing robotic devices for hand rehabilitation presented in this Chapter, describes the movements trained by each robot, the ROM and range of force/torque of each DOF, and mentions devices that have been clinically evaluated with stroke subjects. Finger ROM in flexion/extension are defined for the MCP joint. The origin corresponds to a position where the proximal phalanx is aligned with its corresponding metacarpal, positive values represent flexion and negative values extension.

The main conclusions of this review are that existing devices have limited ROM or forces, which prevent the use of the robot for subjects suffering from spasticity requiring high forces to open the hand. Exoskeleton and glove systems are difficult to install and to adapt to stroke subjects with different hand sizes and impairments. End-effector based interfaces, i.e. which subjects grasp during exercises in contrast to exoskeletons, may offer a more flexible solution with fewer mechanical constraints, corresponding better to manipulation of real objects. Current commercially available products for hand rehabilitation only provide passive training. Passive movement may increase mobility and prevent joint stiffness. However, active movements generated and controlled by the subject are necessary to increase muscle strength, joint coordination and stimulate motor learning. Finally, only a few devices have been clinically evaluated with stroke subjects, but they have produced positive results that motivate the development of new devices dedicated to hand rehabilitation (Takahashi et al., 2008; Hesse et al., 2003; Adamovich et al., 2005; Hesse et al., 2008).

2.5 Discussion

Stroke survivors can improve their ability to walk, use their affected limbs and carry out ADL with greater skill, by intensively practicing exercises that activate neural and muscular mechanisms. However, among the different approaches and therapies proposed, it is still

Table 2.1: Specifications of principal existing robotic devices for hand rehabilitation (in italic, data estimated from the literature).

robotic device	movements trained with the robotic device	ROM of each DOF	forces/ torques	clinical trials
Hand Robot Alpha-Prototype II (Masia et al., 2007)	finger flexion/extension (all together)	*0–45°*	120N	no
ARMin hand module (Nef et al., 2006)	wrist flexion/extension	-30–75°	3Nm	no
	forearm pronation/supination	±70°	4Nm	
GENTLE/G system (Loureiro and Harwin, 2007)	finger flexion/extension (4 fingers together, 2DOF)	0–70°	18N	no
	thumb flexion/extension	-10–60°	12N	
HWARD (Takahashi et al., 2005)	finger flexion/extension (4 fingers together)	25–90°	15N	yes
	thumb flexion/extension	0–60°		
	wrist flexion/extension	0–20°		
BiManuTrack (Hesse et al., 2003)	forearm pronation/supination or wrist flexion/extension	*±180°*	5Nm	yes
Gifu Haptic Interface (Kawasaki et al., 2007)	finger flexion/extension (individual, 2DOF)	0–90°	5N	no
	finger abduction/adduction	0–45°	5N	
	thumb flexion/extension (2DOF)	0–80°	5N	
	thumb abduction/adduction	0–60°	5N	
	wrist flexion/extension	±90°	1.3Nm	
	forearm pronation/supination	±180°	3Nm	
Rutgers Master II (Bouzit et al., 2002)	finger flexion/extension (3 fingers and thumb individually)	*0–40°*	16.4N per finger	yes
Finger Trainer (Hesse et al., 2008)	finger flexion/extension (4 fingers individually)	$*$	$*$	yes
Amadeo system (Kollreider et al., 2007)	finger flexion/extension (5 fingers individually)	*0–70°*		no

$*$: no available data

not clear what is optimal for each patient. Nevertheless, some key points to improve stroke rehabilitation have been identified (Dobkin, 2008; Daly and Ruff, 2007):

- Rehabilitation should clearly start as early as possible after the stroke, to take advantage of high neuroplasticity for strengthening "good connections".
- On the other hand, rehabilitation should also be used in the chronic phase where plasticity is lower, as further improvement is still possible (Buetefisch et al., 1995). Indeed, intensive use of the impaired hand for task specific activities benefits stroke subjects, even in the chronic stage several years after the stroke, and leads to improvements in independence, speed and precision (Underwood et al., 2006).
- Exercises requiring active participation of subject should be given preference, to activate neural pathways, build muscle strength, increase endurance and coordination.

A crucial point is to develop solutions to increase the intensity of therapy stroke subjects receive, especially in the chronic phase, to extend the recovery process, without increasing the costs of rehabilitation. New approaches such as drug treatment and FES have produced promising results for certain types of impairments; however this can not be generalized to all patients, and the potential benefits of these techniques still need to be proven.

The overview of the different programs proposed in rehabilitation centers illustrates the importance that robotic devices now have for rehabilitation. Robots are not only used as assessment tools to measure and analyze parameters, such as gait parameters, but they now actively participate to the rehabilitation and interact with patients to exercise walking and balance. Moreover, the new developments in robot-assisted rehabilitation are promising, with several devices dedicated to the training of wrist, hand and finger function.

Robotic devices may be an ideal complement to augment the amount of therapy provided to stroke survivors. However robot-assisted rehabilitation is relatively new, and although the potential may be large, benefits of robots for rehabilitation after stroke still have to be investigated.

Chapter 3

Design of Robots for Rehabilitation of Hand Function

Restoring hand function is critical for stroke survivors to regain independence and social integration. Based on our knowledge of impairments following stroke, and of existing rehabilitation devices, three new robotic systems have been developed: the *Delta Workstation*, the *HandCARE*, and *t*he Haptic Knob (Lambercy et al., 2006; Milner et al., 2007). These three robots aims at training specific tasks which include those stroke survivors desire to recover most (Peterson, 2004), and that are currently not addressed by existing robotic interfaces for rehabilitation. The *Delta workstation* trains handwriting and fine object manipulation, the *HandCARE* exercises finger movement and fractionation required for typing, and the *Haptic Knob* simulates grasping and knob manipulation.

This chapter presents the biomechanical constraints for the development of robotic devices for hand rehabilitation resulting from our studies on hand parameters with healthy and post-stroke subjects. The developments of the *Delta workstation*, the *HandCARE* and the *Haptic Knob* are presented. In the following sections, particular attention will be given to the design and development of the *Haptic Knob*, as it is the main contribution of this thesis.

3.1 Philosophy

We oriented the development of our robotic devices for the treatment of chronic stroke subjects, who have at least partial motor function of the arm and shoulder as a result of spontaneous recovery. Design is thus oriented towards subjects capable of at least minimal movement with the hand (Lambercy et al., 2007).

Because of extensor muscle weakness, the hand of stroke survivors is often locked in a closed position and they are not able to control its motion well. Thus, one of the first functions which robotic devices for hand rehabilitation should train is opening of the hand. Next, the reverse operation i.e. closing of the hand and applying suitable force to grasp objects should be trained. Sufficient versatility of the robot is required to allow individual movements for each finger, grasping with all five fingers, or more precise functions such as pinching between two fingertips or tripod pinch. In addition, the manipulation of objects frequently involves lifting the arm, forearm pronation/supination and application of isometric wrist torque together with grip force. Training this coordinated action has not been addressed with previous interfaces.

To address all of these fundamental tasks, we decided to develop three robotic devices based on an end-effector approach, i.e. that subjects hold and manipulate but that is not fixed to the hand. The advantage of using three robotic devices is the simplification of design constraints, as each device can be dedicated to a specific activity. Later, therapy can be personalized to the subject by selecting a combination of exercises with each robot, in order to train all of the tasks, with an increased focus on those related to subject's impairment.

3.2 Biomechanical Constraints

The design of a rehabilitation tool must take into account human biomechanics and consider the impairments resulting from stroke to allow natural and comfortable movements. Simple experiments with 8 healthy and 5 post-stroke subjects were performed to identify hand parameters such as maximum grasping force, wrist torque and maximum hand aperture, and to describe how humans interact with various objects during prehension (Fig. 3.1). The results of these investigations are summarized in the following points (Lambercy et al., 2007):

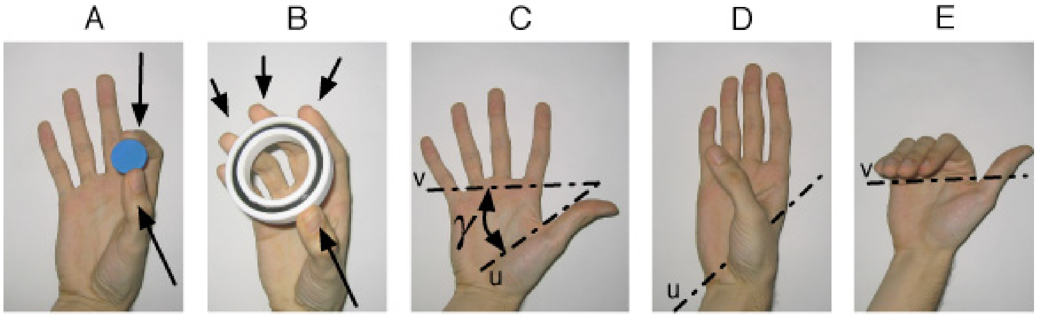

Figure 3.1: Main functions and movements of the fingers. A: Pinch is the closure of the thumb against one or two other fingers. It is one of the hand functions that stroke survivors most desire to recover. B: The grasp generally involves the thumb and at least two fingers. C: Dashed-lines u and v represent the axes of rotation of the thumb (D) and of the four other fingers (E), respectively. The angle γ between these axes and movement of the thumb varies with each person (adapted from Lambercy et al., IEEE TNSRE, 2007).

- Various types of prehension are commonly used in ADL; *grasping*, i.e. enclosing an object with all fingers, *pinching*, i.e. prehension only with the thumb and the index finger, *tripod*, i.e. prehension with the thumb, the index finger and the middle finger, *lateral pinching*, using the side of the index finger in opposition to the thumb. Robotic devices for hand rehabilitation should consider these fundamental types of prehension and offer adapted training options.

- The size and shape of the hands vary from one person to another. The design of robotic devices should allow easy adaptation to any type of hand, i.e. the attachments supporting the fingers should be adaptable to the subject so that movements are comfortable.

- Functional rehabilitation of the hand aims at training fine manipulations that do not require high force levels. Typical ADL, such as opening or closing a jar require torques of 0.7 Nm or less, while pinching and manipulating small objects typically require forces smaller than 20 N (Table 3.1) (Forssberg et al., 1991; Smaby et al., 2004).

Table 3.1: Typical activities of daily living

torque to open a jar	0.7 Nm
pinch force to hold a fork (Smaby et al., 2004)	11.0 N
pinch force to manipulate a key (Smaby et al., 2004)	7.0 N
grip force to lift a 200g weight (Forssberg et al., 1991)	3.8 N
finger force to type on a keyboard (Rempel et al., 1994)	3.5 N
grip force to hold a glass (Van Dijck et al., 2006)	1.0 N

- Thumb and fingers have different roles during hand activities; the thumb is often considered to be the most important digit of the hand, allowing opposition with the other fingers for prehension, and producing the majority of forces and torques during ADL such as holding and turning a key (Van Dijck et al., 2006).

  The thumb and the opposing four fingers do not move along the same axis during grasping. The angle γ between the rotation axes of the thumb and the other fingers (Fig. 3.1C) varies up to -45° for the left hand, and $+45^\circ$ for the right hand, and is different for each person. Furthermore, the orientation of these axes depends on the task. For example, they are oriented in different directions during grasping and pinching.

  Moreover, the thumb generally moves at the same speed as the other fingers during opening and closing of the hand. However, for some people, thumb movement is slower, leading to an asymmetrical movement.

- The orientation of the fingers during movement is different for healthy and post-stroke subjects because of limited finger abduction of the latter. To investigate this, healthy and post-stroke subjects were asked to open the hand until the fingers were maximally extended at the MCP joint and then to close the hand until the fingertip of the thumb touched the fingertips of the four opposing fingers. The movement of the fingertips was constrained to a plane. To determine the natural orientation and amplitude of finger movements, measurements were made when the five fingers were at the extreme open and closed positions. Figure 3.2 presents the orientations as well as the amplitudes of the finger trajectories. The orientation angle of the thumb is significantly smaller in stroke subjects. Due to joint stiffness, muscle contracture, flexor synergy or spasticity, the stroke subjects were all unable to place the thumb in opposition to the other four fingers. The five stroke subjects had difficulty in opening the hand, but in terms of passive range of motion, there was no notable difference with healthy subjects (Dovat et al., 2007).

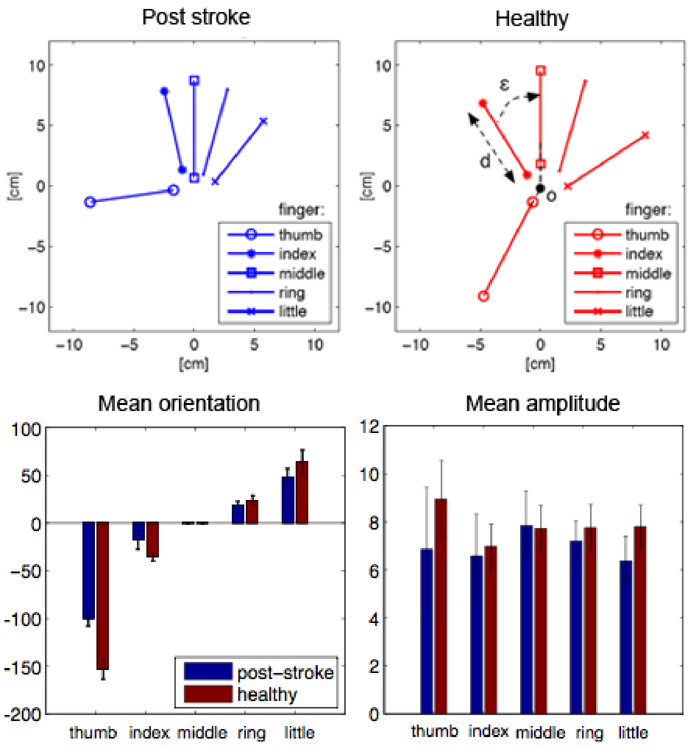

Figure 3.2: Mean orientation with middle finger as reference and amplitude of the five fingertip trajectories for eight healthy and five post-stroke subjects. The error-bars are the standard deviations (adapted from Dovat et al., ICORR, 2007).

- During grasping, all the fingertips move in approximately the same plane. This is in contrast to the movement of only one finger where the fingertip follows a circle around the MCP joint.

Table 3.2 summarizes some essential hand parameters, for healthy and post-stroke subjects. These values and the different points listed in this section defined the constraints for the design of robotic devices for hand rehabilitation.

Table 3.2: Quantification of hand properties

	healthy subjects	stroke subjects
maximum hand aperture (thumb to middle finger)	180.0 mm	180.0 mm
maximum rotation of forearm	180.0 deg	180.0 deg
maximal grasping force (male)	450.0 N	240.0 N
maximal grasping force (female)	300.0 N	120.0 N
maximum wrist torque (pronation/supination)	20.0 Nm	$*$.

$*$ no available data

3.3 The *Delta Workstation*

Training handwriting and object manipulation requires fine wrist control while holding an object such as a pen, but also arm movement to support and position the hand. Additionally, lifting the arm during reaching, which is a component of most ADL, should be implemented as part of robotic systems if they are to provide effective therapy (Dovat et al., 2008b). Therefore, the objective was to develop a robotic interface that combines grasping with shoulder and elbow movement in order to *(i)* increase muscle strength in the arm, *(ii)* improve the ability to control the movement during a reaching activity and *(iii)* improve the coordination between shoulder, arm and hand muscles.

Inspired by previous work on a robotic assistant to train writing of Chinese ideograms (Teo et al., 2002), the rehabilitation system was developed around a Delta robot from Force Dimension[1] (Fig. 3.3). The interface has 6 active DOF, 3 translations and 3 rotations, and can provide continuous forces up to 20 N and torques up to 0.2 Nm in a workspace of $30 \times 30 \times 30\ cm^3$. This not only allows movements that are large enough to involve shoulder and elbow while manipulating the end effector of the robot, but also fine rotations of the wrist in a way to simulate handwriting. A specially designed fixture allows different objects, e.g.

[1]Force Dimension, Lausanne, Switzerland, http://www.forcedimension.com

pen, sphere or card, to be attached to the end effector of the robot (Fig. 3.3) for more realistic interactions.

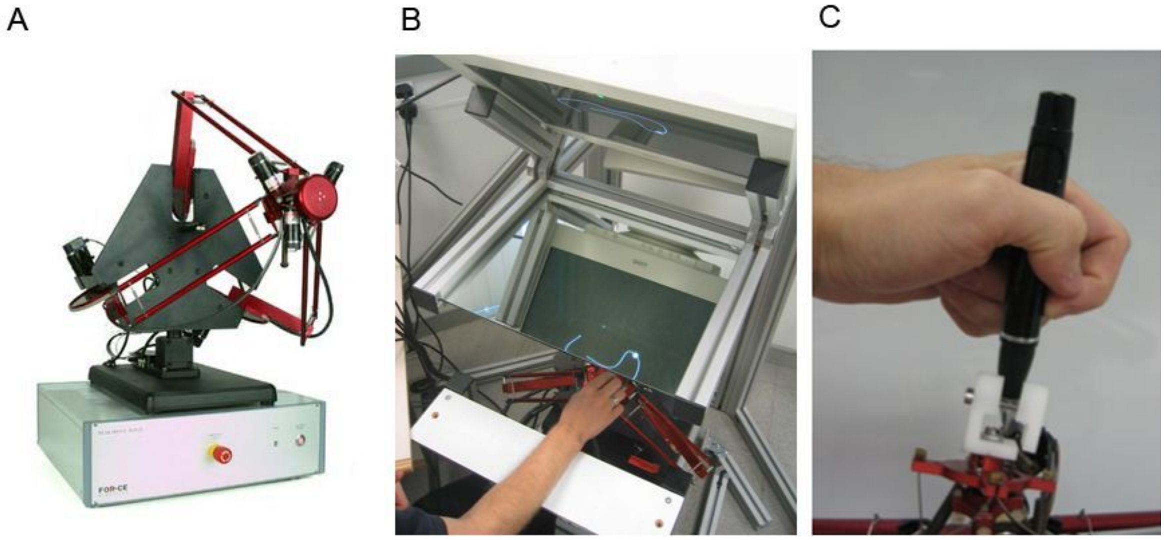

Figure 3.3: A: 6-DOF Delta force feedback device from Force Dimension (http://www.forcedimension.com). B: Virtual reality workstation with a mirror for collocation of visual and motor workspaces. C: Custom built fixture with a pen for handwriting training (adapted from Dovat et al., Virtual Rehabilitation, 2008).

The robot is mounted on a custom built workstation with a mirror, used to create a reflected image of the computer monitor in which the visual and motor spaces coincide. A VR environment, in which the subject manipulates the virtual object/pen is implemented using Microsoft Visual C++.

Shoulder and elbow training typically consisted in moving virtual objects from one point of the workspace to another, avoiding virtual obstacles to force the subject to lift the arm. Training of handwriting defined specific paths subjects had to follow by moving the virtual pen on a virtual table created by the robot.

3.4 The *HandCARE*

For completeness, a brief description of the *HandCARE* is given here. Typing, like many other ADL, requires finger flexion and extension, but more importantly the control of individual finger movement. Because of synergies in muscles flexing the fingers this task is especially difficult for stroke survivors, since fingers all move together most of the time. The objective is thus to develop a robotic interface that can train finger flexion and extension for each finger individually in order to *(i)* decrease muscle tone in finger flexors, *(ii)* improve the ability to control the force generated by each finger, *(iii)* improve the coordination between fingers while performing a grasping task.

Cable interface designs such as the SPIDAR (Yanlin et al., 2003) or the Mantis Workstation developed by Mimic[2], which have shown the high potential of cable-based haptic interfaces, attracted our interest and served as a starting point for our design. The *HandCARE* is a Hand Cable Assisted REhabilitation (CARE) system, where each finger is attached to a cable loop allowing predominantly linear displacement, in accordance to observations presented in Section 3.2. The interface can assist or resist the subject in finger extension and flexion movements (Dovat et al., 2008).

The workspace of the *HandCARE* consists of five linear paths of 8 cm length corresponding to a finger extension/flexion angle range of 0-70° at the MCP joint (for a finger length of 9 cm). The maximal opening is 19 cm and the minimal closing is 1.5 cm between thumb and the opposing fingers. A clutch system allows switching between three actuation modes for each finger, so that the subject can train a variety of combinations of finger movements, e.g. with five fingers or with the tripod thumb-index-middle. The maximal continuous force that can be generated is ± 15 N per finger, while inherent friction is less than 0.8 N in any position of the workspace. With the differential sensing system, each force sensor can measure forces between ± 15 N, with a sensitivity of 0.2 N.

Training with the *HandCARE* typically consisted of individual isometric finger force generation, to exercise individual finger control. Grasping with the whole hand was also trained, where fingers should be actively flexed and extended in a coordinated pattern (Dovat et al.,

[2]http://www.mimic.ws/mantis.html

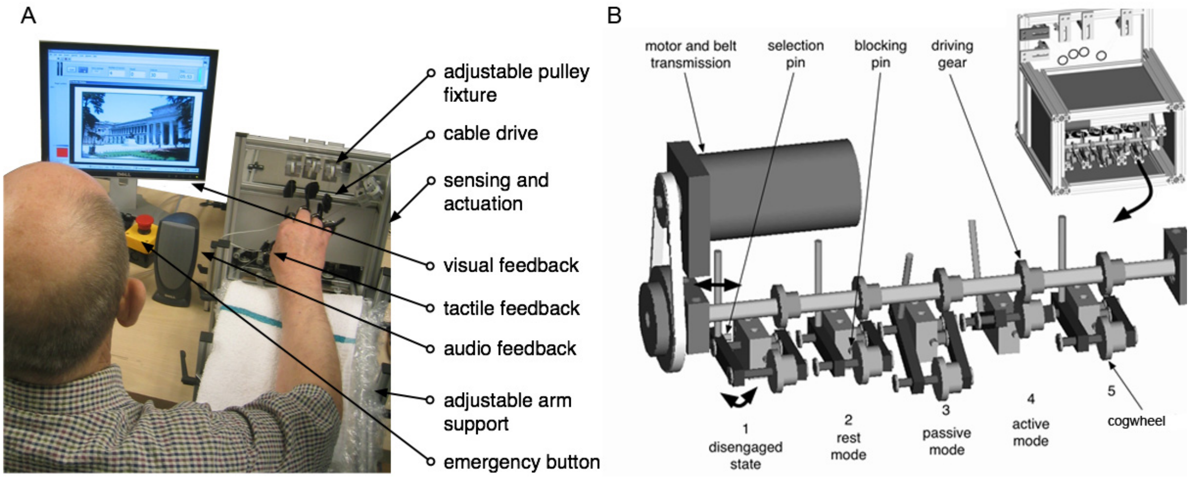

Figure 3.4: A: The main part of the interface is the clutch and control box, which includes sensing and actuation systems as well as the clutch systems. Five adjustable pulley fixtures allow the direction of the movements to be modified. Visual, tactile and audio feedback are implemented to keep the subject informed during the training.The dimensions of the interface are 60 × 30 × 30 cm^3 (arm support included). B: Details of the clutch mechanism allowing three operation modes for each individual finger: i) rest mode - the cogwheel and the cable are blocked by a pin and the finger cannot move (clutches 2 and 5), ii) passive mode - the cogwheel is free to rotate so the finger can move freely (clutch 3), and iii) active mode - the cogwheel is driven by the motor, which moves the finger (clutch 4). In order to select the mode, a pin is engaged in one of three positions corresponding to the described modes (Dovat et al., 2008) (adapted from Dovat et al., IEEE TNSRE, 2008).

2007, 2008a). Additional details on the design and implementation of the *HandCARE* system can be found in Ludovic Dovat's NUS PhD dissertation, *A system for robot-assisted rehabilitation of hand and finger function after stroke* (Dovat, 2009).

Further, a second version of the *HandCARE* has later been developed, implementing several new features (Dovat et al., 2008c): a new push-pull cable system for the movement of fingers, decreasing friction and allowing 3-dimensional movements of fingertips; the integration of a second motor, to offer a wider range of possible training protocols; the automatisation of the clutch system using servomotors; and the use of force sensors located at the output of the robot, i.e. at subject's fingertips.

3.5 The *Haptic Knob*

3.5.1 Objectives

Buttoning and knob manipulation require coordination of grasping with wrist and forearm rotations. Therefore, the objective is to develop a rehabilitation robot with 2 DOF; one rotation for the forearm and one translation to simulate grasping, compatible with the properties relative to the hand listed in Section 3.2.

As a complement to the two other robots presented in previous sections, the *Haptic Knob* should focus on *(i)* decreasing muscle tone in flexor muscles of the hand and wrist, *(ii)* increasing control and strength of grasping, *(iii)* improving forearm pronation and supination range, and *(iv)* training coordination of different degrees of freedom.

3.5.2 Concept

Prior to the design of the robot, experiments were performed with 8 healthy subjects to study grasping. Subjects were asked to grasp and rotate two cylindrical objects with diameters of 3 *cm* and 6 *cm*, while the position of fingers and forces applied were estimated. Instinctively, subjects used a different number of fingers to grasp an object depending on the size of the hand and of the object (Ruffieux, 2006). However, the analysis of the position of the fingers around the cylindrical object during grasping demonstrated that, independently of the number of fingers involved, the thumb could always be separated from the other fingers such that the thumb and fingers formed a jaw, with the thumb applying high forces in opposition to other fingers (Fig. 3.5). Therefore, the design did not need to consider all fingers individually.

Several designs for a 2 DOF haptic knob were analyzed and evaluated in (Dovat et al., 2006), and are described in the next points as well as in Figure 3.6. The selected design and its implementation are described in (Lambercy et al., 2007) and in the next Sections.

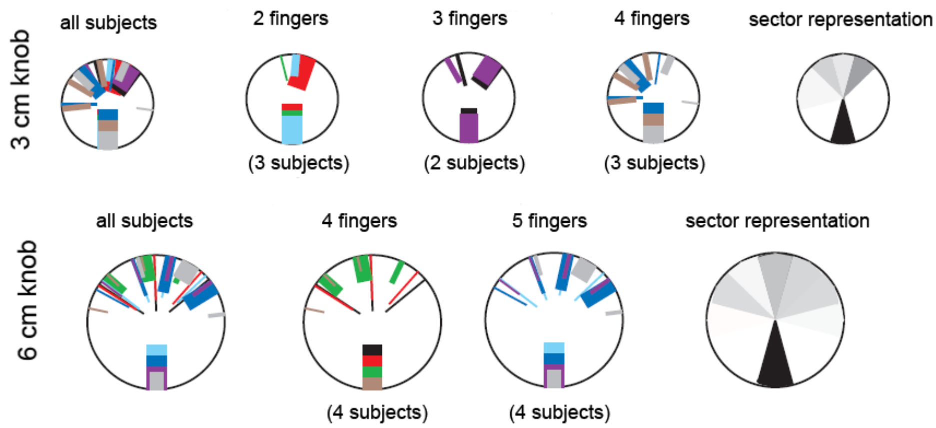

Figure 3.5: Knob grasping; finger positions (colored lines, one color per subject) and normalized force applied by each finger (thickness of the line, thicker lines representing higher forces) for 8 healthy subjects. This determines which fingers are involved in grasping. The graphics to the right of each row show a sector representation of the finger positions as a function of the force applied. The color intensity indicates the importance of this knob section during a grasping or pinching movement (black: very important, white: not important) (adapted from Ruffieux, EPFL Master Thesis, 2006).

High pressure balloon:

A first potential design considered two finger supports actuated by a high pressure balloon and preconstrained by a rubber band, as shown in Figure 3.6A. This design is very intuitive, easy to implement and has good mechanical properties (low friction, mechanic play and inertia). However, the lack of durability, the difficulties in controlling pneumatic transmissions and the small movement amplitude precluded the use of this kind of system as rehabilitation tool.

Cam system:

The second concept was based on a cam, as shown in Figure 3.6B, whose actuation generates the opening of the knob by the radial variation of the cam diameter. This design is interesting because of the excellent mechanical properties (low inertia and high rigidity) and simple control. The disadvantages are the limited range of motion and the inability to modify parameters without changing the complete system.

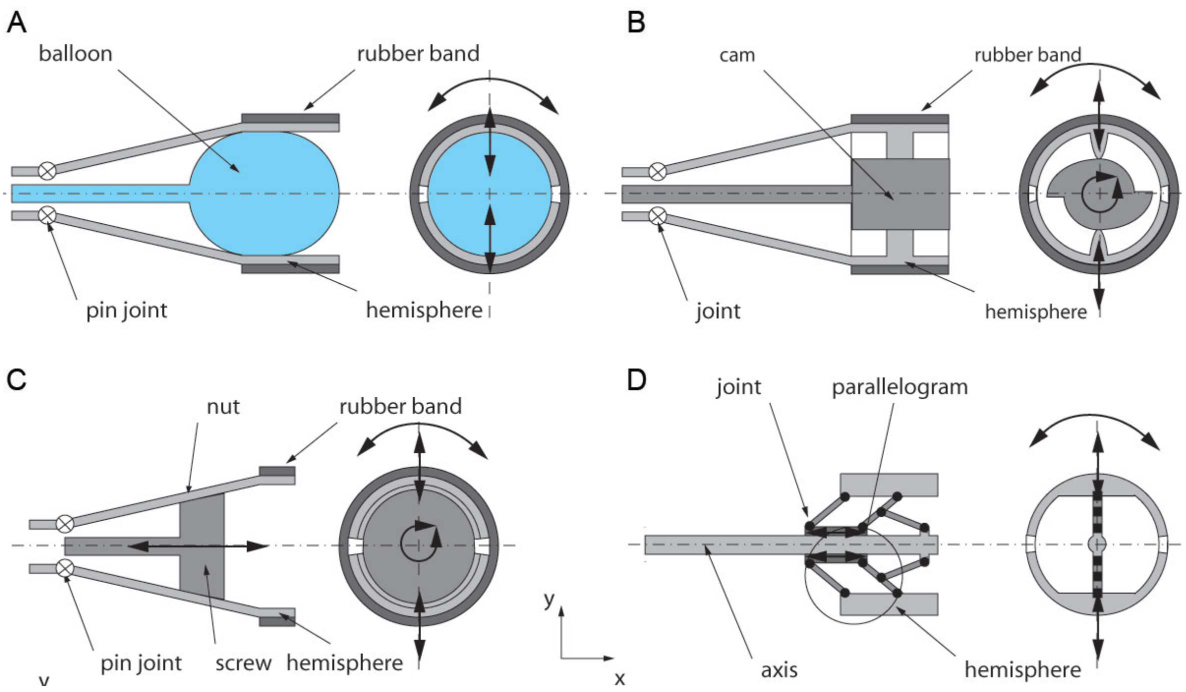

Figure 3.6: A: Haptic knob with pneumatic balloon: the balloon is pressurized to open the two finger fixations, while a rubber band pulls and closes them. B: Haptic knob using a cam: during the rotation of the cam, the variation of its diameter opens the knob. C: Haptic knob with "journal-assembly" system: the translation in x-direction of the nut is transformed into the opening of the knob in y-direction. D: Haptic knob with parallelogram structures: the parallelogram transforms a linear displacement in x-direction into a displacement in y-direction (adapted from Dovat et al., IROS, 2006).

Journal-assembly system:

Another solution was to use a journal-assembly system (Fig. 3.6C); the translation of the nut, actuated by the screw, opens the knob. The control for this configuration is basic, although the two different movements, knob opening and forearm rotation, are achieved by means of a differential (i.e. the screw and the nut must move with the same speed to have only a knob rotation). The main disadvantages are the high friction due to nutscrew transmission (reduced if play is increased) and the small opening.

Parallelogram system:

The final proposed design consisted of two parallelogram systems, as shown in Figure 3.6D. This mechanism is similar to that of an umbrella: linear displacement of the parallelograms in x-direction is transformed into perpendicular motion in y-direction. The inertia of the complex parallel structure is high, but a classic control approach and large and variable opening range are possible. This system is also the only one offering the possibility to obtain a linear translation in the y-direction (for the hand opening), as the others have only a single pivot resulting in an undesired movement in the x-direction. Moreover, the parallelogram system does not require any spring or rubber band to constrain the finger supports and can generate forces in both directions, thus enabling control in both opening and closing directions of the hand.

The four designs presented in this section were evaluated by 6 engineers involved this project, according to the following four criteria:

- mechanical properties: friction, inertia, durability
- degrees of freedom: number of DOF (rotation and translation) and range of motion
- flexibility: adaptability of the interface to different users
- control of the system: depends on the type of actuators and transmissions

Table 3.3 compares the design solutions proposed in this section. The parallelogram system appeared to be the most suitable for our application and has thus been implemented. The resulting system, called the *Haptic Knob*, is presented on Figure 3.7.

This system can generate forces in both opening and closing directions. One actuator is used to control the translation of a linear belt drive responsible for the linear opening, and another one rotates the system. The inertia of the complex parallel structure is larger than with the other possible designs presented. However, this is not a critical factor as the targeted

Table 3.3: Qualitative comparison table for the proposed designs based on the evaluation of 6 engineers involved in the project: grades between 1 (poor) and 4 (excellent).

design	mechanical properties	degrees of freedom	flexibility	control	**total**
high pressure balloon	3	1	3	1	**8**
cam	4	1	1	4	**10**
journal-assembly	2	2	3	3	**10**
parallelogram	2	4	3	3	**12**

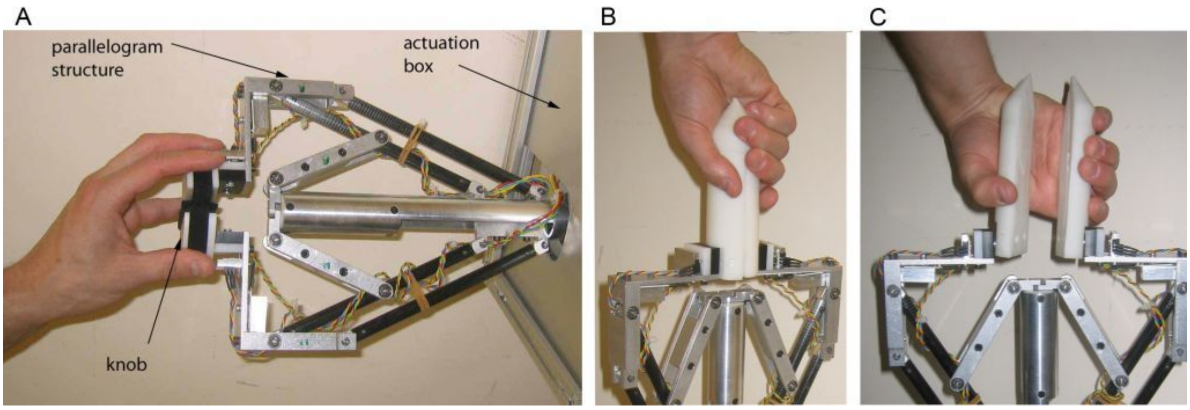

Figure 3.7: 2 DOF *Haptic Knob* for hand rehabilitation. A: Parallelogram structure equipped with four force sensors located close to the output, allowing measurement of grip and insertion force. Dimensions of the interface are $60 \times 30 \times 25$ cm^3. Different fixtures can be used to interact with the subject, depending on the level of impairment. A cone mechanism mounted on the *Haptic Knob* can be used to train a complete opening movement, from a strongly contracted and closed hand (B) to a widely opened position (C) (adapted from Lambercy et al., IEEE TNSRE, 2007).

movements involve only a slow forearm rotation, i.e. low angular acceleration, and the large opening amplitude made this mechanism attractive for our purpose.

3.5.3 Kinematics

The *input* parameters of the system are the displacement of the linear actuator z_{in} and the rotation angle θ_{in} of the second actuator (Fig. 3.8). The *output* parameters are the aperture of the knob r_{out} and the knob angle θ_{out}. The differential direct kinematics are given by:

$$\underbrace{\begin{bmatrix} \dot{r}_{out} \\ \dot{\theta}_{out} \end{bmatrix}}_{output} = \underbrace{\begin{bmatrix} \frac{2d-z_{in}}{\sqrt{z_{in}(4d-z_{in})}} & 0 \\ 0 & \frac{1}{2} \end{bmatrix}}_{Jacobian} \underbrace{\begin{bmatrix} \dot{z_{in}} \\ \dot{\theta_{in}} \end{bmatrix}}_{input} \tag{3.1}$$

where d is the length of one parallelogram rod as shown in Fig. 3.9. The Jacobian is a diagonal matrix, as the outputs r_{out} and θ_{out} are independent of each other. Singularities occur if the determinant of the Jacobian equals zero or infinity. In our case, there are three singularities, when the opening angle of the parallelogram $\alpha = 0°$, $90°$, $180°$ (Lambercy et al., 2007). As α is between 15° and 75° in our design, these singularities are outside of the reachable workspace, and hence pose no problem.

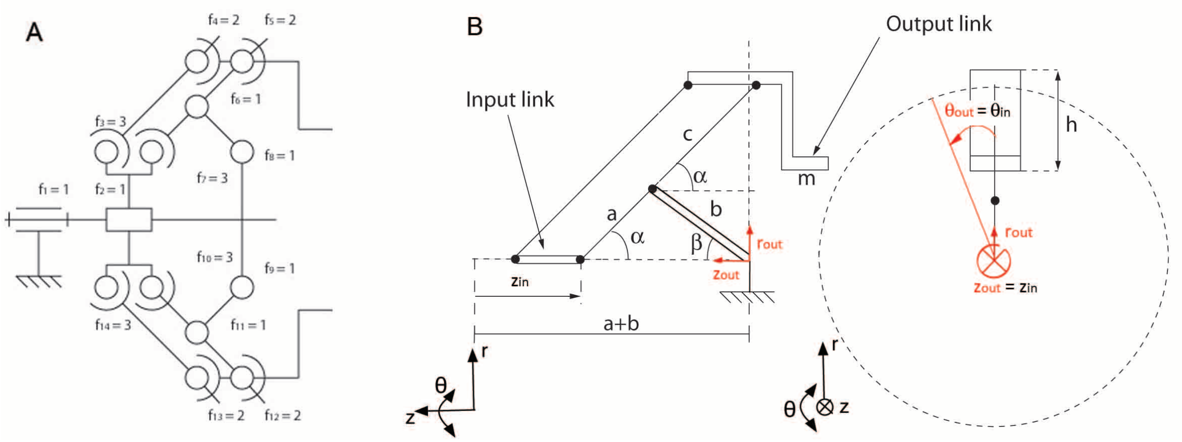

Figure 3.8: A: Kinematic model of the parallelogram system. B: Diagram of one parallelogram arm. α is the opening angle of the parallelogram, a; b, and c are the lengths of the parallelogram components. In our case $a = b = c = d$, where no parasitic movement in the z-direction is observed, m is the endpoint of the system and h is the distance between the endpoint and the top of the interface (adapted from Lambercy et al., IEEE TNSRE, 2007).

To determine if the system is overconstraint, the number of degrees of freedom of the output N_{DOF} can be determined using Grubler's criterion for closed mechanical chains:

$$N_{DOF} = 6(n_l - 1) - \sum_{i=1}^{l}(6 - f_i) \tag{3.2}$$

where n_l is the number of links in the system (including the base), l is the number of joints and f_i is the number of degrees of freedom of the i^{th} joint.

In our case $n_l = 11$, $l = 14$ and the numbers of DOF f_i are shown in Figure 3.8A, yielding $N_{DOF} = 2$. The kinematic chain has two degrees of freedom and is thus not overconstrained.

3.5.4 Design Features

The angle γ corresponding to the mean orientation of the thumb (Fig. 3.1C) is adaptable to each subject: the knob has been designed to allow rotation of one of the two finger supports up to $\pm$ 45°, as shown in Figure 3.9A. It is also possible to vary the velocity of one finger support. The velocity depends on the distance between the two parallelograms and the velocity of one finger support can be adjusted by shifting the carriage (δ) as illustrated in Figures 3.9B and 3.9C.

Fixtures of various shapes can be attached to the interface in order to train different hand functions. In particular, buttons of different diameters with special finger supports to fix the hand between the two parallelograms can be used to train interaction with objects.

Materials were chosen based on their mechanical properties, weight and comfort for the user. The cylinders for the rotation and translation are made from aluminum, the parallelograms are of carbon fiber to reduce the inertia, and the fixtures are of polyoxymethylene (POM), offering the subject a comfortable grip. The external dimensions of the interface are $60 \times 30 \times 25$ cm^3 for a total mass of 12 kg (including actuators, power supply and electronics).

3.5.5 Actuation

A brushed DC motor M_1 (Maxon RE40, 150 W; encoder 2000 $counts/rev.$; gear GP42C, ratio 15:1; control card EPOS 24/5), actuates the linear displacement to open and close the

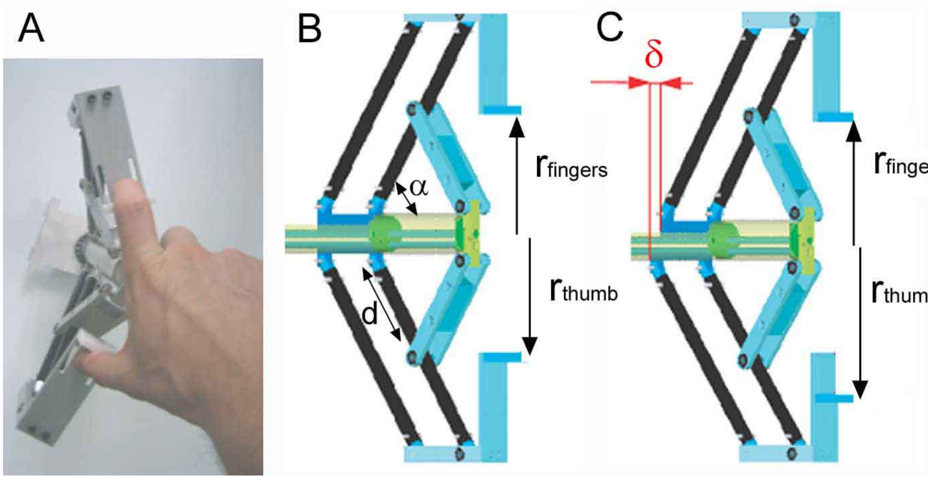

Figure 3.9: Adjustable orientation of one parallelogram within a range of ±45° allows the orientation of the finger supports to be adapted to any hand. B: With two symmetric parallelograms, the displacements of the thumb (r_t) and the fingers (r_f), as well as the velocity of the two endpoints are similar. C: By shifting the carriage (δ), the displacement of the thumb support (r_t) is different from the displacement of the finger support (r_f). The maximal opening is 15 cm (adapted from Lambercy et al., IEEE TNSRE, 2007).

Haptic Knob. The rotation of the motor axis is converted into a translational movement by a commercial linear belt drive module (Minimodule MLM-9, Schneeberger AG, Switzerland, 11 mm/rev) with a moving carriage fixed to a belt. The belt is driven by a pulley fixed on the motor shaft. The linear movement of the carriage is transmitted to two internal rods to which the two parallelogram structures are fixed. (Fig. 3.10). These rods slide inside the central aluminum tube, and are guided by two linear bearings fixed inside the tube. The linear bearings are made of POM to minimize friction during the sliding of the rods .

A similar motor M_2, but with a reduction ratio of 4.3:1, actuates the rotation of the knob. A belt transmits the rotation of the motor axis to the axis of the interface, with a reduction ratio of 2:1.

The position of the output of the *Haptic Knob* is measured with the motor encoders. The relations linking the motor outputs q_1 and q_2, and the output of the interface, r_{out} and θ_{out}

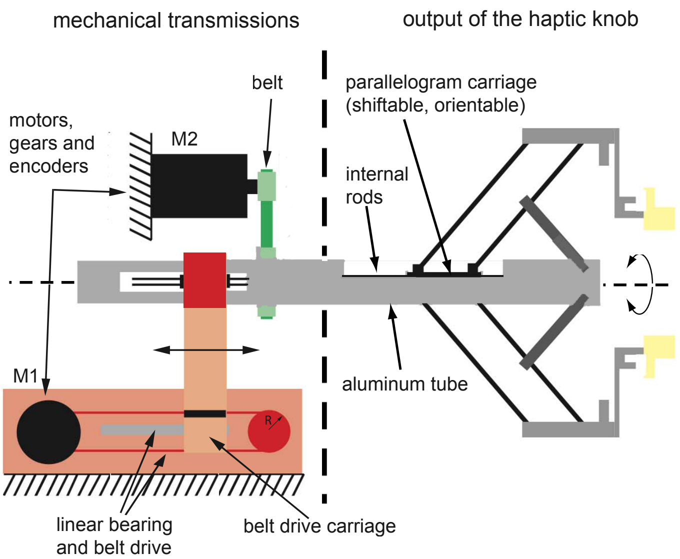

Figure 3.10: Details of the mechanical transmissions for the two DOF. A linear bearing is used for the linear DOF, and a belt for the rotational DOF (adapted from Lambercy et al., IEEE TNSRE, 2007).

are given by:

$$
\begin{aligned}
r_{out} &= \sqrt{\frac{2\pi R}{r_1} q_1 \left(4d - \frac{2\pi R}{r_1} q_1\right)} - h\,, \\
\theta_{out} &= \frac{q_2}{r_2\, r_3}\,,
\end{aligned}
\tag{3.3}
$$

where r_1 is the reduction ratio of motor M_1, R the radius of the pulley fixed on the shaft of motor M_1, r_2 the reduction ratio of motor M_2, r_3 the reduction factor selected for the belt transmission and h the distance between the top of the parallelogram and the position of the finger fixation (Fig. 3.10).

The inverse kinematics (derived from Equ.(3.3)) are:

$$
\begin{aligned}
q_1 &= \frac{r_1}{2\pi R}\left(2d - \sqrt{4d^2 - (r_{out} + h)^2}\right)\,, \\
q_2 &= r_2\, r_3\, \theta_{out}\,.
\end{aligned}
\tag{3.4}
$$

3.5.6 Sensors

Four force sensors (Millinewton 2N, LPM-EPFL, Fig. 3.11A) are used to measure the grasping force F_g and perpendicular force F_p applied by the user during movement. These sensors use the piezoresistive properties of thick films. The sensing element is an alumina cantilever with a thick-film piezoresistive Wheatstone bridge and is soldered onto a thick alumina base, which contains the (thick-film) conditioning circuit (Maeder et al., 2005; Birol et al., 2005). A deformation of the sensing cantilever is translated into a variation of voltage. In our configuration, the sensors can measure grasping and perpendicular forces of up to 30 N with a resolution of 0.2 N. The linearity error of these sensors is smaller than 1%FS (Full Scale). The electronics integrated on the base of the sensor amplifies the signal and output a voltage which is a linear function of the force.

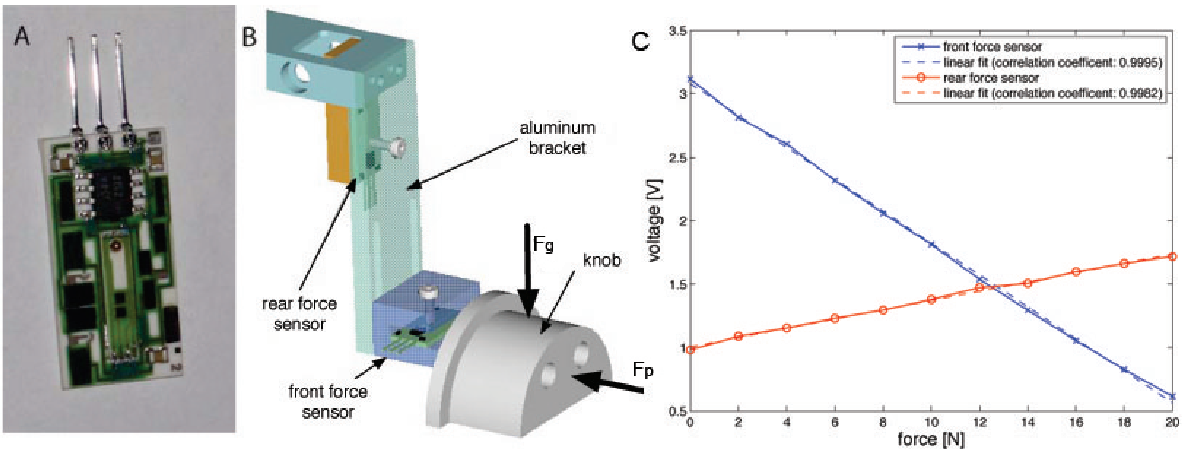

Figure 3.11: A: Millinewton force sensor (LPM-EPFL). B: Position of the force sensors on one of the parallelogram structure of the robot. Two other sensors are placed in a symmetrical way on the second parallelogram structure to measure force applied on both sides of the Haptic Knob. C: Calibration curves for the front and rear force sensors (adapted from Lambercy et al., IEEE TNSRE, 2007).

One force sensor is attached to each support fixture of the *Haptic Knob* (front force sensors, Fig. 3.11B). The force is measured in an indirect way: the sensor is preloaded with a screw touching the sensor cantilever to adjust the initial offset for bidirectional measurements. The grasping force applied by the user deforms the finger fixation support, which induces a displacement of the cantilever. The two other sensors (rear force sensors) are placed under the aluminum brackets on which the finger supports are mounted (Fig. 3.11B). They measure the flexion of the fixation support during interaction with the *Haptic Knob*, and can also determine the force perpendicular to the opening direction, along the axis of rotation (z-direction). Both front and rear force sensors are measuring grasping forces F_g, but only the rear sensors are sensitive to perpendicular forces F_p allowing proper decoupling of these two forces. Figure 3.11C presents the calibration curves of the force sensors, which demonstrate their linearity. The calibration of the force sensors was performed by applying different forces F_g at the center of the finger support, where subjects will place the fingers during exercises with the Haptic Knob.

3.5.7 Control

The *Haptic Knob* is connected to a PC (Pentium 4, 4 GB RAM, 233 MHz). Control and feedback techniques are implemented in LabView 8.2 (National Instruments), in a multirate timed-loop structure with a high priority control loop at 100 Hz and a low priority visual feedback loop at 20 Hz. This control frequency is sufficient because only slow movements are performed with the *Haptic Knob*. Figure 3.12 presents the architecture of the control program. Data from the EPOS controllers of the two motors (positions, velocities and current) are transferred to the main program over a RS232 protocol. Data from force sensors are sampled at a frequency of 1 kHz, through a data acquisition card (PCI-6221, National Instruments).

Impedance control is used for the two DOF, with friction compensation for the opening/closing mechanism. Linear friction was compensated with a linear function as shown in Figure 3.13. The sign of this feedforward compensation is in the direction of the movement performed by the subject, which is inferred from the force applied by the hand to the knob. In this way, different force effects can be created to resist or assist the subject's movements.

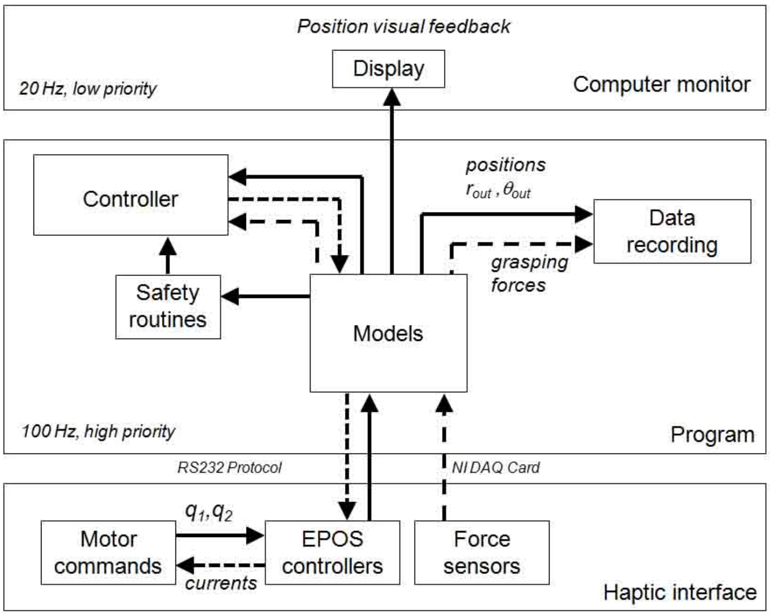

Figure 3.12: *Haptic Knob* control diagram (adapted from Lambercy et al., IEEE TNSRE, 2007).

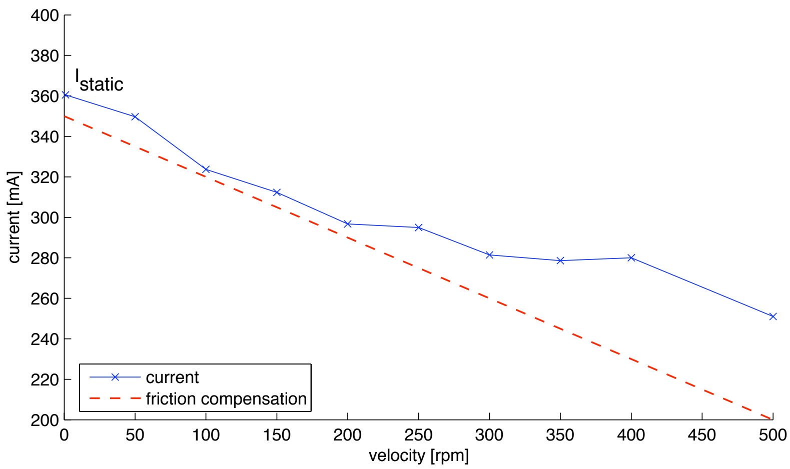

Figure 3.13: Identification of friction in the linear DOF and feedforward command implemented to compensate the friction (dashed line) (adapted from Lambercy et al., IEEE TNSRE, 2007).

3.5.8 Safety

Interacting with human subjects requires a high level of safety; movements should be limited to the range of motion of the user, and mechanical stops should prevent undesired movement of the robot. Further, redundant emergency switches should allow the user and the operator of the *Haptic Knob* to quickly stop the robot at any time.

To prevent any harm or damage, both software and hardware emergency systems have been implemented (Gassert et al., 2006). Redundant safety is realized through:

- Mechanical travel limitations for the two degrees of freedom of the interface to prevent excessive opening (r_{out} >15 cm) or rotation ($|\ \theta_{out}\ |$>180°).
- Velocity, acceleration and forces are limited by software safety routines that monitor motor output in order not to harm the user.
- Electronic end-of-travel switches that stop the translational module before reaching the mechanical travel limits to prevent impacts on the travel limits.
- A main power interruptor, that can be actuated by the human subject during the experiments, by means of a pneumatic emergency bellows, as well as by the experimenter by means of a standard emergency pushbutton switch.
- Low-level security surveillance routines embedded in the motor controllers. This allows the experimenter to set speed, acceleration and force limitations in advance. If the high-level control generates commands that exceed these limits, the motor controllers will automatically stop the motors and alert the experimenter, independent of any malfunction of the high level control.
- The position of the subject in front of the device prevents interference of the fingers with the parallelogram structure. In addition, knobs attached to the structure have a protection barrier to restrain the fingers from touching the force sensors.

3.5.9 Arm support

Stroke subjects may move parts of the body other than the hand and finger during exercises to compensate for impairments. To ensure that this does not happen, the arm and elbow of the subject are placed on an adjustable support fixed to the device (Fig. 3.14). If necessary, the arm can be strapped to the support to prevent subjects from lifting the arm or rotating the trunk while performing the exercises. A cushion was placed on the arm support for increased comfort.

Figure 3.14: Arm support of the *Haptic Knob*. Distance to the knob, height and orientation of the arm support can easily be adjusted to the subject.

3.5.10 Performance evaluation

Specifications:

The active workspace of the *Haptic Knob* is a ring with outside and inside diameters determined, respectively, by the maximal and minimal opening of the device (Fig. 3.15). These parameters can be modified using special fixtures which can be mounted on the interface. With no fixture, maximal opening of the *Haptic Knob* is 150 mm while the minimal opening is 30 mm. The fingers can also be attached to the inside of the parallelogram structure, and thus reduce the minimal radius. The range of motion in rotation is $\pm 180°$.

Friction affects the sensitivity and dynamics of the interface and the quality of the interaction with the user. The static friction torque for the rotation of the *Haptic Knob* is less than 0.02 Nm. The static friction for the opening/closing amounts to 9 N due to the linear

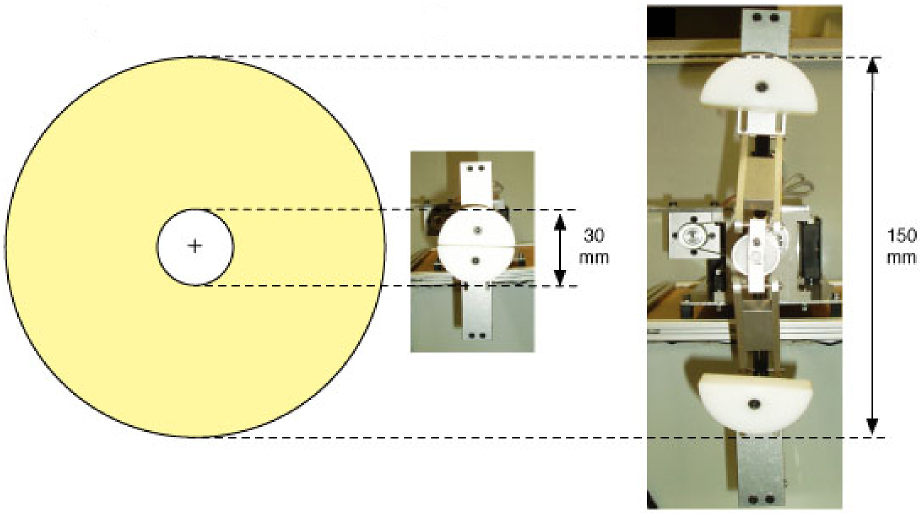

Figure 3.15: Interface workspace: the active workspace of the *Haptic Knob* is defined by two circles in the same plane, with a diameter of 30 *mm* when it is fully closed, and 150 *mm* when it is fully opened (adapted from Lambercy et al., IEEE TNSRE, 2007).

module and the carriages. Friction on this axis was estimated by measuring the mean motor current required to open or close the device at a constant velocity (Fig. 3.13). Friction can be reduced by applying a compensative force F_{comp} with the motor which is composed of a static term F_{static} determined by I_{static} and a velocity dependent term determined by the slope of the curve on Figure 3.13. The sign for the friction compensation is inferred from the signal recorded by the front force sensor F_g, which determine the direction of the desired motion.

$$F_{comp} = sign(F_g)(F_{static} - D_f \cdot v) \tag{3.5}$$

Figure 3.16 illustrates the effect of the friction compensation during a closing movement with the *Haptic Knob*. With compensation, the interaction force decreases dramatically to less than 1 N. Figure 3.16 also shows the effects of two constant resistive forces on the grasping force applied by the a healthy subject during closing movements.

The maximal constant opening or closing force that can be generated by the haptic inter-

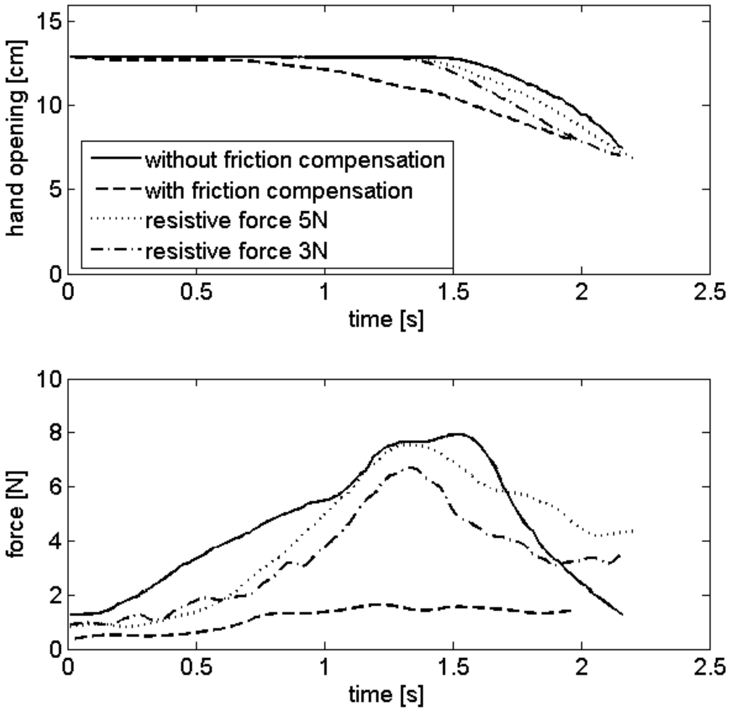

Figure 3.16: Closing movement of the *Haptic Knob* for a healthy subject without and with the friction compensation, and with the addition of constant resistive forces of 3 N and 5 N (top). Corresponding grasping forces during the four trials (bottom) (adapted from Lambercy et al., IEEE TNSRE, 2007).

face is 50 N, while the maximal constant torque is limited to 1.5 Nm. These values satisfy requirements to train typical ADL, as defined in Table 3.1. Table 3.4 summarizes the specifications of the *Haptic Knob*.

Opening of the hand

Stroke subjects have different levels of impairment and the interface can offer exercises adapted to each subject. The output of the interface can be changed to offer knobs of different diameters or shapes (Fig. 3.17). The fingers can also be fixed inside the parallelogram structures to train grasping of real objects that can be placed in the palm of the user, and allow complete closing

Table 3.4: *Haptic Knob* specifications

maximum opening of the robot (without knob)	150	mm
minimal opening of the robot (without knob)	30	mm
workspace of one finger (MCP extension ϕ)	60	deg
maximum rotation of the robot	± 180	deg
maximum rotation of the moving parallelogram	± 45	deg
maximum generated opening/closing force	50	N
maximum generated torque	1.5	Nm
friction force for the linear DOF	9	N
friction torque for the rotation DOF	0.02	Nm
inertia (closed position)	$4.83 \cdot 10^{-4}$	Kgm^2
inertia (open position)	$19.3 \cdot 10^{-4}$	Kgm^2
force measuring range	30	N
force measuring sensitivity	0.2	N
control frequency	100	Hz
force sensors sampling frequency	1000	Hz
external dimensions	$60 \times 30 \times 25$	cm^3
mass (with actuators, power supply and electronics)	12	kg

(Fig. 3.17B).

Figure 3.7 shows a cone mechanism mounted on the haptic interface to help stroke subjects with a high level of spasticity open and close the hand. The cone mechanism, similar to tools used in rehabilitation centers, allows the subject to sweep the hand along the form to gently open it, then the *Haptic Knob* can provide assistance to attempt the opening movement. The device can thus assist complete hand opening, beginning from a strongly contracted and closed hand. The four force sensors can measure the force along the cone during the positioning of the hand as well as the force during the opening movement, which may provide a novel method of assessment for hand rehabilitation.

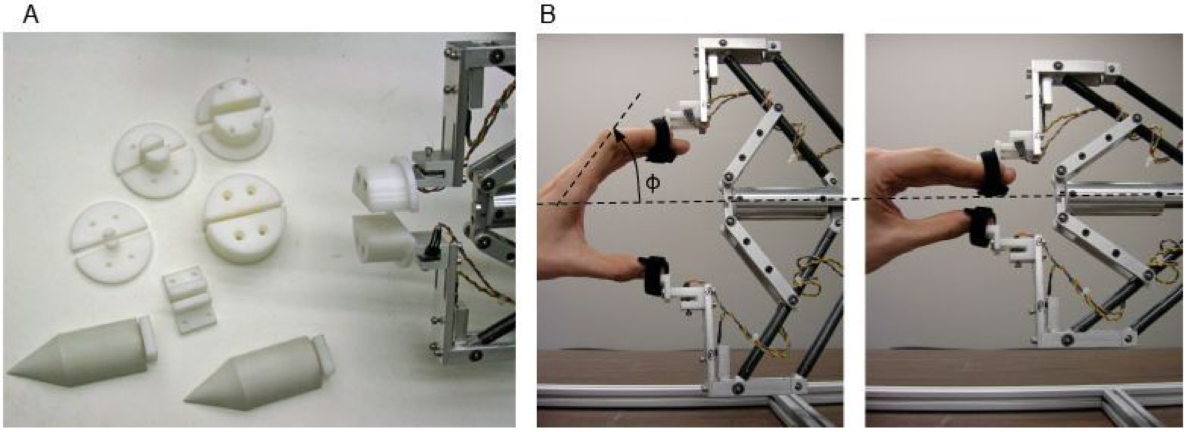

Figure 3.17: A: Different fixtures can be mounted on the output of the *Haptic Knob*, including knobs of different diameters (from 1 *cm* to 7 *cm*), a fixture to train lateral pinching, and a conical grip B: Fingers can also be fixed inside the parallelogram structures to train grasping of real objects. The workspace of the hand starts from a closed position where the fingers are touching the thumb, to a 60° MCP extension ϕ (adapted from Lambercy et al., IEEE TNSRE, 2007, and Lambercy et al., ICORR, 2007).

Interface forces and torques

The dynamic performance of the interface is adequate to generate force and torque as functions of position and velocity. Figure 3.18A,B shows the effect of a velocity dependent torque

$$\tau = D\,\dot{\theta}_{in} \tag{3.6}$$

implemented on the rotational DOF of the *Haptic Knob*. Positive damping ($D > 0$) produces a velocity dependent resistive torque and can be used to strengthen the muscles. Conversely, negative damping ($D < 0$) can produce a velocity dependent assistive torque to help subjects with weak muscles extend their range of movement.

Figure 3.18C shows the effect of destabilization produced by a position dependent torque

$$\tau = K\,\theta_{in} \tag{3.7}$$

Negative stiffness ($K < 0$), as in this figure, can be used to amplify movement error. Positive

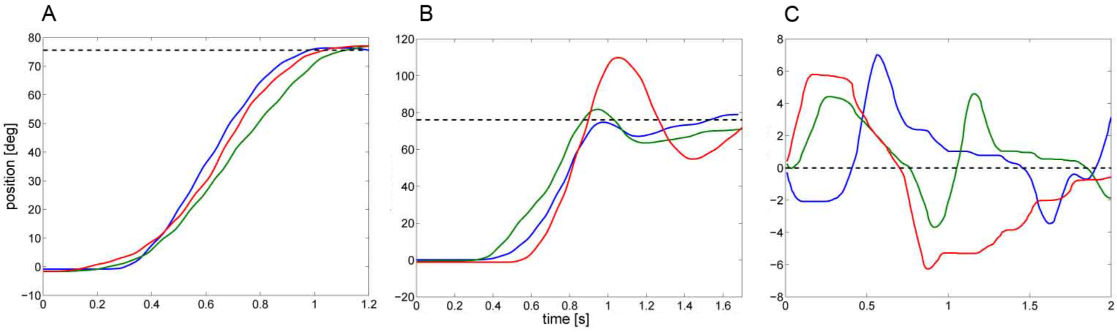

Figure 3.18: Rotation movements of a healthy subject interacting with the *Haptic Knob*. The dashed lines represent the target position. A,B: Movements with a velocity dependent resisting torque(A) and with a velocity dependent assisting torque (B). C: Position-dependent torque which creates an instability around a target position (adapted from Lambercy et al., IEEE TNSRE, 2007).

stiffness can guide movement along a desired path or drive the hand so as to teach and modify movement. Impulse perturbations can also be generated to study reflexes or estimate impedance. Similar effects are possible with the linear DOF of the *Haptic Knob*.

3.6 Discussion

Three robotic system have been designed and developed for hand rehabilitation; the *Delta Workstation*, the *HandCARE*, and the *Haptic Knob*. Each robot is focused on the training of specific ADL which are among those stroke subjects desire to recover the most. The interfaces take into account the biomechanical properties of the human hand and the physical impairments resulting from stroke; the systems are flexible to adapt parameters such as ROM, force/torque and hand fixation/handles for comfortable interaction and adapted training.

Compared to existing robotic devices for rehabilitation presented in Section 2.4, the developed systems offer the advantage of exercising the principal hand functions both actively or passively. Large ROM and large resistive, or assistive, forces can be applied to create haptic effects that can improve training. Furthermore, robots are flexible and can easily adapt to different subjects with various level of impairment, making therapy with these robots available to a wide range of subjects.

Such robot can be used independently, but the real advantage of these devices is their complementarity, offering robot-assisted rehabilitation at all levels of the upper limb, i.e. the arm, the wrist and the fingers. Further, this gives a wide range of solutions for physiotherapists to customize the therapy in function of the level of impairment of the subject for improved efficiency.

The *HandCARE* and the *Haptic Knob* are very compact end-effector robots, easy to setup and to use, and could easily be integrated into a domestic environment to provide home rehabilitation. Additionally, special care has been given to the external appearance of the devices for the comfort and security of subject and therapist.

Chapter 4

Exercises for Robot-Assisted Rehabilitation

Interactive, motivating and task oriented exercise programs are critical for subjects to use a rehabilitation robot to its full potential. Indeed, exercises determine the way subjects interact with the robot, define tasks to perform and the intensity of treatment, and more importantly maintain motivation to train.

This chapter discusses the constraints related to the design and implementation of useful exercises for robot-assisted rehabilitation, and presents the strategies used to develop exercises with the *Haptic Knob*.

4.1 Exercises strategy

Passive and active exercises are currently used in robot-assisted rehabilitation, with a number of subcategories with robots producing assistive or resistive forces fields. Typically, at an early stage during stroke recovery, movements such as finger extension could only be performed passively, i.e. the robot has to move the fingers in order to compensate for the weakness in finger extensors observed in stroke subjects (Kamper and Rymer, 2001). Passive movements are believed to improve joint, muscle and tendon mobility, while at the same time reducing muscle tone (Hesse et al., 2003).

However, passive movements driven by robotic interfaces may not be sufficient to offer good rehabilitation. While contribution from passive movements maintains passive properties of joints and muscles, active movements initiated by the subject are required to improve the strength and coordination between muscles, and promote correct patterns of muscle activation and coordination (Hogan et al., 2006; Woldag et al., 2007).

Other types of exercises to train force generation are necessary, such as interactions with loads which have been shown to reduce muscle weakness (Kahn et al., 2006). Active movements against resistive forces may be a good strategy to improve motor function of the hand after stroke (Lambercy et al., 2007b).

Further, active participation of the subject during training is fundamental to skill acquisition (Winstein et al., 2003). Motor recovery after stroke is considered as a form of motor learning, where undamaged brain regions are recruited to generate motor commands to the same muscles that were used before the injury. A method is thus to apply motor learning principles observed in healthy subjects to improve stroke rehabilitation. In this sense, therapy should focus on intensive repetition of active movements where subjects interact with various force fields to help develop control strategies to optimally perform the required task (Krakauer, 2006; Reinkensmeyer et al., 2004).

To favor learning, exercises should be challenging but not too difficult to perform, and task oriented exercises enable subjects to easily understand and identify them with daily activities (Colombo et al., 2006). Our strategy is to decompose complex tasks into combinations of simple subtasks to be trained individually, so that each exercise focuses on one single function, e.g. grasping or turning a knob, on which subjects can concentrate. Simplicity of exercises also helps decrease the "fear of the robot" that is commonly observed in subjects who are not used to interacting with machines.

4.2 Motivation for training

Classical physiotherapy and robot-assisted therapies are based on intensive movement repetitions involving the impaired limb. These movements require significant effort by the subject and may be painful and tiring. Additionally, after several repetitions, subjects may get bored, decreasing concentration and motivation to train, and directly affecting the quality of the therapy.

Motivation is important to insure that subjects are training at their full potential during therapy sessions, pushing the limits imposed by their impairment. But motivation is even more important for stroke survivors at home, where they have to cope with their disabilities, force themselves to involve their impaired limb in ADL and increase their physical activity. Psychological factors, sometimes referred to as positive emotions, have an impact on the recovery process (Ostir et al., 2008) and should be considered in the design of rehabilitation exercises, and later during the therapy. This implies constant interaction between therapist and subject, to encourage and inform the subject on his/her progression. During robot-assisted rehabilitation, a similar relationship between the robot and the subject should be created. The robot should interact to reassure the subject, and guide him/her through the rehabilitation process, giving positive and motivating feedback.

4.3 Feedback techniques

The *Haptic Knob* can provide various types of feedback to be used in rehabilitation exercises (Fig. 4.1). Feedback can help the realization of a task by interacting with the user, but it is also an active part of the rehabilitation process, stimulating motor learning (Poole, 1991).

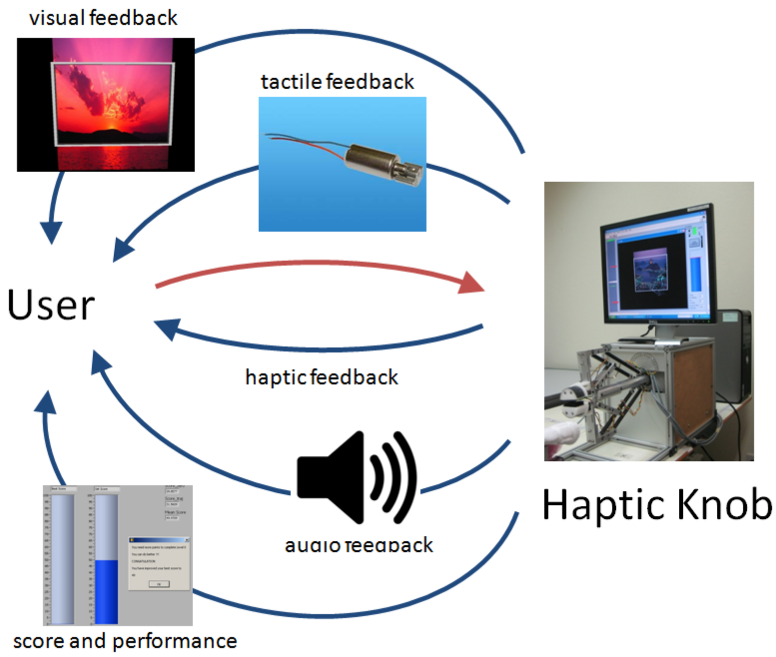

Figure 4.1: Feedback techniques implemented on the *Haptic Knob*.

4.3.1 Visual feedback

Visual feedback is commonly used in robot-assisted rehabilitation systems (Crosbie et al., 2007), and is probably the simplest way to interact with a user. For example, basic visual feedback is used with the MIT-MANUS, where blinking targets indicate to subjects where to move the handle of the robot (Krebs et al., 2004). On the other hand, more complex feedback is implemented with the Rutgers Master II, or the GENTLE/G system, where subjects move the hand, or arm, in a 3-dimensional virtual environment (Adamovich et al., 2003; Loureiro et al., 2003).

Visual effects are ideal for keeping subjects motivated, are generally easy to understand and associate to the trained task, and can easily be customized to the user. Moreover, exercises with visual feedback or virtual environments may improve the outcome of post-stroke rehabilitation, by augmenting subjects' awareness of their actual performance and promoting visual-motor coordination (Merians et al., 2002; Chern et al., 2002; Henderson et al., 2007;

Holden, 2005).

Visual feedback can also be used to improve performance during rehabilitation by helping subjects push the limits of their ability by using visual feedback distortion, i.e. visual feedback corresponding to force or distance can be gradually changed by an imperceptible amount to encourage improved performance (Brewer et al., 2008). This can typically help stroke subjects in the chronic phase, who often demonstrate learned nonuse, i.e. the tendency to use affected limbs below their true capability, to improve their performance without being consciously aware of it.

Complex virtual environments can be implemented to simulate interaction with virtual objects or home environments, however we believe it is more essential to offer simple visual information that can easily be understood by the subject, and associated with the task being trained. Exercises with the *Haptic Knob* use basic visual feedback composed of selected pictures that are visually distorted or modified in orientation as a function of the action on the robot. In addition to being simple to implement, this solution offers the interesting possibility for the subject to incorporate his/her own pictures, to further increase motivation and interest for the therapy (Lambercy et al., 2007b).

4.3.2 Somatosensory feedback

Haptic feedback is essential for post-stroke rehabilitation. Somatosensory function is commonly impaired after stroke; subjects typically have difficulties in detecting forces, and localizing their hand in space, which directly affects movement planning and execution (Connell et al., 2008). Robotic devices such as the *Haptic Knob* have the advantage of providing haptic feedback, i.e. specific force and/or torque patterns that can stimulate proprioceptive sensors in the skin, joints and muscles to increase subjects' awareness and use of somatosensory information. Similarly, tactile feedback can be used to restore sensation on the impaired limb; typically small vibrator motors, similar to vibrators in cellphones, can be taped on subject's hand or arm to stimulate the skin when a task is successfully performed (Burdea, 1996).

4.3.3 Psychological feedback

Finally, another type of feedback actively contributes to the learning process: we define *psychological feedback* as the information given to subjects by therapists and the robotic system, regarding the quality of the performance. Robots can advantageously record and quantify subject's performance and provide subjects and therapists with a real time evaluation, typically by giving a score, commenting on the task, or comparing it with previous performance. This simple type of feedback not only maintains motivation, but also informs the user about movement errors, and where it is possible to improve.

Audio feedback is also a possible method of motivating subjects, however audio signals introduce several problems; subjects may easily be distracted by other environmental noises, and hearing may be deficient in elderly subjects. Furthermore, precautions should be taken when choosing feedback techniques for rehabilitation exercises. Indeed, the dominance of visual feedback in sensory integration is a recognized fact. Vision typically dominates haptic and tactile feedback for the perception of shape, limb position and stiffness. Somatosensory information however has priority for texture recognition (Brewer, 2006). Consequently, to design rehabilitation exercises, special care should be given to the amount of visual feedback. Typically, the use of visual information should be avoided, or limited, for exercises devoted to training somatosensory function.

4.4 Discussion

Exercises for robot-assisted rehabilitation should focus first on the reduction of impairments, i.e. spasticity and limited ROM, by providing passive training for movements that are too difficult to perform for subjects. However, active participation and interaction with various force fields is preferred whenever it is possible, to further increase muscle strength and control of the impaired limb, and facilitate skill acquisition and retention. Motor rehabilitation may also benefit from technologies and training environments that enhance the use of proprioceptive and sensory feedbacks (Liebermann et al., 2006). Exercises should thus be simple but task-oriented, with interactive feedback to keep subjects motivated and concentrated.

The optimal solution for developing motivating rehabilitation exercises is probably to present them as games, with a score indicative of the performance and the possibility of progressing to higher levels of difficulty adapted to the level of impairments. Indeed, therapeutic programs that build on a base of successively more difficult performance and that promote a sense of personal responsibility for these accomplishments is believed to be more successful and motivating (Lewthwaite, 1990; Johnson, 2006). Moreover, contrary to the prevailing view that elderly people do not like video games, it is clear from our experience with post-stroke subjects that they may easily understand and enjoy simple video games.

Based on these observations, three simple exercises for hand rehabilitation have been implemented on the *Haptic Knob*. These exercises train grasping and knob manipulation and are described in Chapter 5. Similar exercises, with simple visual feedback and intuitive interactions have been developed with the *HandCARE* and the *DELTA Workstation* to exercise finger fractionation, finger coordination, handwriting and pick and place tasks (Dovat et al., 2007, 2008b).

Chapter 5

Pilot Study

With the aim of evaluating the potential of the *Haptic Knob* as a rehabilitation tool, a pilot study has been conducted at Simon Fraser University (SFU) in Canada, where 4 post-stroke subjects participated in a 2 month therapy program, consisting of a combination of exercises with the three robotic devices presented in Chapter 3. The goals of this preliminary study were to investigate the feasibility of using the *Haptic Knob* as part of a rehabilitation program, analyze the reactions of stroke subjects to the training with robotic device, and quantify a potential reduction of impairment resulting from the proposed therapy.

This chapter describes the three exercises developed with the *Haptic Knob*; (i) the *opening/closing exercise*, to train grasping, (ii) the *pronation/supination exercise*, to train object and knob manipulation, and (iii) the *force modulation and proprioception exercise*, to train control of grasping force and somatosensory information. The protocol of the experiment is also detailed in this Chapter, and results of exercises with the *Haptic Knob* and their effects on subjects' impairments are discussed.

5.1 Methods

5.1.1 Subjects

Four chronic post-stroke subjects i.e. more than 6 months after stroke (3 males and 1 female, 54-83 years of age) participated in the robot-assisted rehabilitation study. Subjects were all right-handed and had right hemiplegia. They could move the arm and hand, but an impairment of the right hand prevented them from using it to perform many typical ADL. The upper limb impairment was assessed before and after the therapy using the Chedoke-McMaster Impairment Inventory (CMMII) (Gowland et al., 1993), where the impairment is scaled from stage 1 (severe impairment) to stage 7 (mild impairment). Each stage of the CMMII is composed of 3 tasks, involving the impaired limb, that subjects should perform in order to proceed to the next stage. Table 5.1 summarizes baseline information for the 4 stroke subjects who participated to the pilot study.

Table 5.1: Baseline data for the 4 post-stroke subjects involved in the pilot study.

subject	gender	age (years)	time post stroke (years)	affected hand	CMMII initial
P1	M	63	2	right (d)	3+
P2	M	74	4	right (d)	5+
P3	F	83	6	right (d)	3++
P4	M	54	18	right (d)	4++

d: dominant hand
CMMII: Chedocke-McMaster Impairment Inventory
+: task of the next stage successfully completed

A control group (CG) composed of four healthy subjects from the same age population allowed comparison of the performance with post-stroke subjects. The institutional ethics committee (SFU Office of Research Ethics) approved the experiments, and subjects gave written informed consent prior to participation.

5.1.2 Protocol

Prior to the beginning of the therapy, post-stroke subjects were assessed by a physiotherapist, and by their performance with the robotic devices, i.e. the *Haptic Knob*, the *HandCARE* and the *Delta Workstation.* The goal of this preliminary session was to determine whether stroke subjects were capable of using the robots, and which exercises were most adapted for them. A personalized therapy program was then composed by the physiotherapist for each subject, adapted to their impairments, and including at least one of the following exercise with the *Haptic Knob*:

- Exercise 1: opening/closing exercise, to train grasping
- Exercise 2: pronation/supination exercise, to train knob manipulation
- Exercise 3: force modulation and proprioception, to train control of grasping force and somatosensory information

Subjects trained during 16 sessions over a period of eight weeks, with two sessions per week. Each session lasted one hour, during which the subject practiced each selected exercise with the *Haptic Knob* for about 15 minutes. The rest of the session consisted in practicing other tasks with the *HandCARE* and the *Delta Workstation* to provide therapy at each level of the upper limb, i.e. arm, wrist, hand. For each exercise, subjects performed 3 sets of 10 movements/repetitions. In order to prevent fatigue, a one-minute rest period was given between each set.

The *Haptic Knob* was placed on a table in front of the subject, with a monitor to display visual feedback during the exercises. Subjects sat in an adjustable chair, placed the right hand on the robot, and rested the forearm on the adaptable arm support in a comfortable position. The level of difficulty, i.e. the level of resistive torque/force, ROM, accuracy, were adapted to the performance of the subject during the therapy once they reach a plateau. Based on the performance, exercises could be changed providing subjects with a constant challenge. However, the same exercises and parameters were used in the first and last session in order to compare the results between the beginning and the end of the therapy. Subjects did not receive any other form of rehabilitation therapy for the duration of the study.

Healthy subjects in the control group participated in one experimental session using similar settings to the post-stroke subjects.

For each exercise, several parameters were extracted from data collected by the robots to evaluate the evolution of subject's performance. A Student's t-test with 5% significance level was performed to determine whether differences in parameters between the successful trials of the first and last sessions were statistically significant.

5.2 Opening/closing exercise

5.2.1 Objectives

The objectives of the opening/closing exercise are to improve grasping function by decreasing flexor muscle tone, increasing finger ROM, and increasing muscle strength in fingers. This exercise is performed using the linear opening DOF of the *Haptic Knob*, while the rotational DOF is held in a static position. The task consists of (i) passive finger extension to open the hand and stretch finger muscles (i.e., the robot opens user's hand) and (ii) active flexion of the fingers initiated and controlled by the subject (Lambercy et al., 2007b).

During the passive phase, the robot opened the fingers to an extended position adapted to subject's ROM determined during a preliminary session, in which the parameters of the exercise were selected. The opening was between 10 and 15 *cm* from the tip of the thumb to the tip of the opposing fingers. At the end of the opening phase, a red indicator on the monitor changed to green to indicate the beginning of the closing phase, which required the subject to actively flex the fingers against a resistive load between 10 to 50 *N* applied by the robot, and adapted to the level of impairment.

In the opening phase, subjects were asked to relax and to apply minimal grasping force to resist the opening. During the closing phase, subjects were asked to control hand closing in order to smoothly reach the target closed position, representing a minimal opening of 1 *cm* between the two jaws of the *Haptic Knob*. A maximal time of 10 seconds was given to subjects to complete the task. When this time limit had passed, the trial was considered as failed and the robot passively completed the movement.

Simple visual feedback was given by means of an attractive picture progressively appearing on the monitor as the subject was approaching the closed position of the *Haptic Knob*. The picture was fully displayed if task was successfully completed (Fig. 5.1).

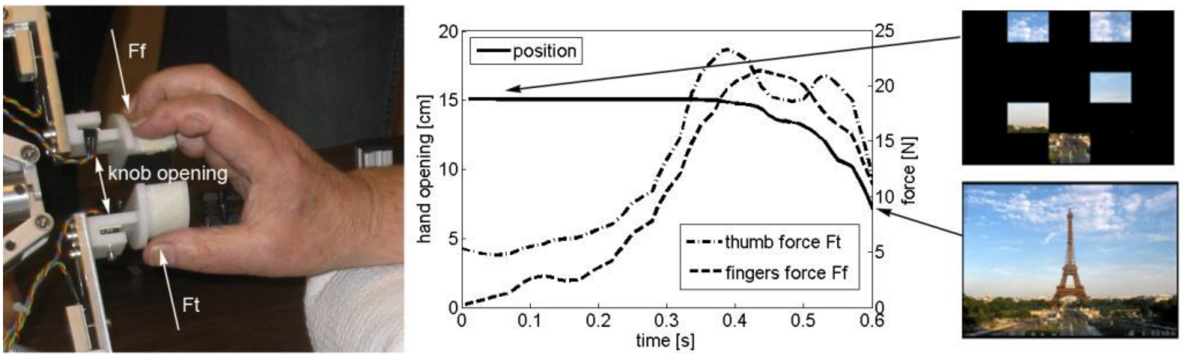

Figure 5.1: Hand position on the Haptic Knob during the opening and closing exercise. Visual feedback was given by means of a picture progressively appearing as a function of the position of the robot (adapted from Lambercy et al., ICORR, 2007).

5.2.2 Data analysis

Muscle tone in flexors of the hand and fingers was evaluated by the resistive grasping force applied by the subject during passive finger extension, i.e. opening phase, respectively F_{ot} for the thumb and F_{of} for the fingers. Ideally, the subject should let the robot open the hand without producing any resistive grasping force.

The *closing movement* was determined from the position waveform using a velocity *v(t)* threshold. Movement onset was defined by:

$$v(t) > 0.02 \cdot \text{median}\{v_{max,i},\ i = 1 \ldots M\} \tag{5.1}$$

where $v_{max,i}$ is the maximal velocity of the i^{th} trial, and M the total number of trials. If a velocity peak occurred at the transition between opening and closing, caused by finger spasticity, it was ignored for the purpose of selecting of the movement onset. The end of the movement was defined by the end of the trial, as the knob reached the closed position.

Two parameters were used to quantify the effects of training:

- movement duration t_m
- motion smoothness was evaluated using the number of zero crossings of the acceleration normalized by the movement duration, denoted n_0. This parameter corresponds to the number of putative submovements comprising the movement, a small number of zero crossings corresponding to a smooth movement (Burdet and Milner, 1998). The acceleration waveform is derived from the position signal filtered with a cut-off frequency of 10 *Hz*.

5.2.3 Results

Subject P1 trained with the opening/closing exercise during the 2 months of robot-assisted therapy. Parameter values are listed in Table 5.2 and can be summarized as follows:

- subject P1 was able to perform the task that consisted in grasping and closing the *Haptic Knob* against the resistive force applied by the robot.
- at the end of the therapy, the time required to close the robot t_m was significantly reduced (-69%), and the maximal closing velocity increased. Subject P1 applied higher grasping forces, forcefully and quickly squeezing the knob during the closing phase. However, P1

Table 5.2: Results of the opening/closing exercise for subject P1 (mean value of each session) and control group CG (mean of two healthy subjects). Improvements in bold correspond to the expectations.

	P1			CG
parameters	session 1	session 16	variation	mean of 2
F_{ot} $[N]$	7.56	7.18	**-0.38 (-5%)**	2.91±2.52
F_{of} $[N]$	7.54	∗8.61	+1.07 (+14%)	2.38±2.19
t_m $[s]$	2.14	∗0.66	**-1.47 (-69%)**	2.63±1.00
n_0 $[1/s]$	7.19	6.74	**-0.45 (-6%)**	7.07±0.19

∗: significant variation

did not control the closing movement, overshooting the target and reaching the travel limitation of the linear DOF of the *Haptic Knob* for almost every trial.

- movement smoothness did not change much as the number of zero crossing of the acceleration did not vary (-6%). However, as the movement is very fast and not well controlled by the subject, this parameter is not representative of the quality of movement.

- mean forces applied by the subject during opening did not change much (-5% for the thumb and +14% for the fingers). These forces are more than 2 times higher than for the healthy subjects from the control group, indicating the presence of finger spasticity.

5.2.4 Discussion

Subject P1 did not perform the opening/closing exercise as expected; instead of trying to control the grasping force during the closing movement, P1 simply squeezed the knob as fast as possible. Although this type of activity may strengthen hand muscles, it does not correspond to the functional task we wanted to train, i.e. controlling the closing movement to smoothly and precisely reach the closed target position. This was probably due to a misunderstanding of the objective during the closing phase of the exercise.

P1 decreased the time required for the closing movement by forcefully squeezing the knob, but results suggest that a decrease in finger and thumb flexor muscle tone, expected from repeated passive extension of fingers did not occur, as resistive forces during opening F_{ot} and F_{of} did not significantly decrease. However, the presence of relatively high grasping forces during opening may also be explained by failure to understand the goal of the exercise by subject P1, as he may already have begun applying grasping force before the end of the opening, in preparation to the closing movement.

To summarize, the opening/closing exercise is feasible in terms of the amount of force to applied by the *Haptic Knob* and comfort of use. However the exercise was not constrained enough, or not comprehensible enough for subject to perform the desired task. A solution to this problem would be to use a position or velocity indicator displayed on the screen to show the user an ideal movement to copy and help him control the closing movement. This solution has been investigated in further studies with the *Haptic Knob* (see Chapter 6).

5.3 Pronation/supination exercise

5.3.1 Objectives

The objectives of this exercise are to train forearm and hand coordination, and improve pronation and supination movements. For this exercise, the *Haptic Knob* remained in the closed position. Subjects were asked to grasp the knob and to supinate (turn so that the palm of the hand faces up) or pronate (turn so that the palm of the hand faces down) the forearm towards a specific target orientation. The amplitude of the movement was selected between 25° to 45° of forearm rotation according to subject's ROM. A resistive torque load adapted to the level of impairment of the subject between 0 to 0.5 Nm was applied by the robot during the exercise so that the knob had to be grasped firmly during the movement. The task required subjects to produce accurate twisting movements to reach the target as quickly as possible.

The target was a ±0.2° window in which the subject had to remain for 0.2 seconds. This small target window required fine motor control at the end of the movement. Visual feedback of the knob orientation was amplified by a factor of 5 in order to promote this fine control. To increase motivation, an attractive picture was displayed whose orientation and brightness were modulated with the angular displacement of the *Haptic Knob* (Fig. 5.2). When the task was successfully completed the picture was correctly aligned with a frame representing the target, which was rewarded by maximum brightness (Lambercy et al., 2007b).

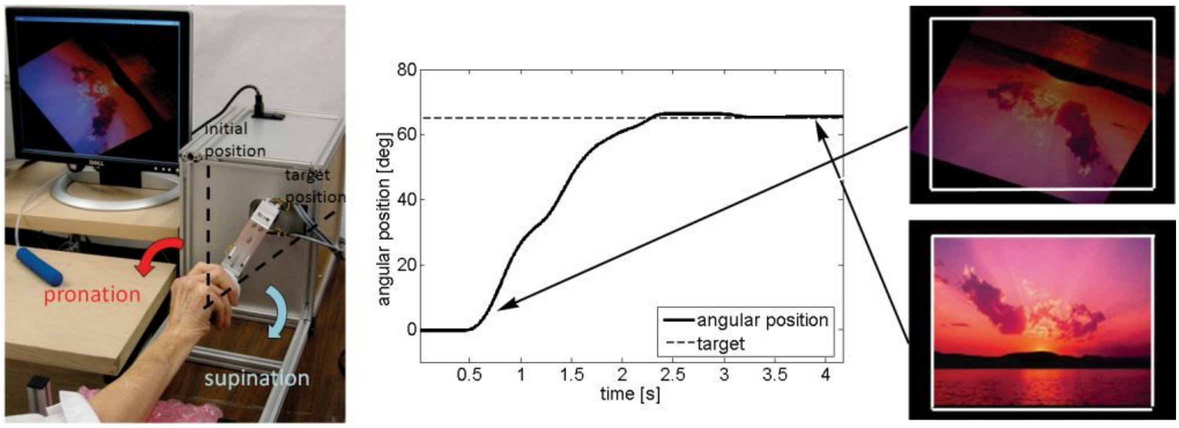

Figure 5.2: Hand position of the *Haptic Knob* during the pronation/supination exercise. Visual feedback was given by means of a picture whose orientation and brightness are progressively modulated as a function of the angular position of the robot (adapted from Lambercy et al., iCREATe, 2008).

If the safety limit was reached during a trial or if the time required to reach the target was more than 15 seconds this trial was considered as a failure and the robot passively completed the movement.

5.3.2 Data analysis

Supination and pronation trials were analyzed independently as the evolution of performance may be different between the two movements.

The *twisting movement* was determined from the forearm rotation angle waveform using velocity $\omega(t)$ and position $\theta(t)$ thresholds. Similarly to the opening/closing exercise, movement onset was defined by:

$$\omega(t) > 0.02 \cdot \text{median}\{\omega_{max,i},\ i = 1 \ldots M\} \tag{5.2}$$

where $\omega_{max,i}$ is the maximal angular velocity of the i^{th} trial, and M the total number of trials. Similarly, the end of the movement was defined by the two conditions:

$$\begin{aligned} &\omega(t) < 0.02 \cdot \text{median}\{\omega_{max,i},\ i = 1 \ldots M\} \\ &|\theta(t) - \theta_T| < 5^\circ \end{aligned} \tag{5.3}$$

where θ_T is the position of the center of the target window.

Two parameters were used to quantify the effects of training:

- the movement duration t_m.
- motion smoothness was evaluated using the number of zero crossings of the angular acceleration normalized by the movement duration, denoted $n0$. In addition, the FFT spectrum of the rotation angle was computed.

Precision in a trial was evaluated in terms of the ability to stay within the $\pm 0.2^\circ$ target window. Two parameters were analyzed once the target window was reached for the first time:

- the time t_{out} spent outside of the target window before completing the task
- the number n_c of crossings in and out of the target window indicating the oscillations around the target window. Ideally this parameter should be 1, i.e. the subject enters the target window only once.

5.3.3 Results

P1 and P3 trained with the pronation/supination exercise. Figure 5.3 illustrates the typical evolution of pronation for P1 during training, and compares it with results of one subject

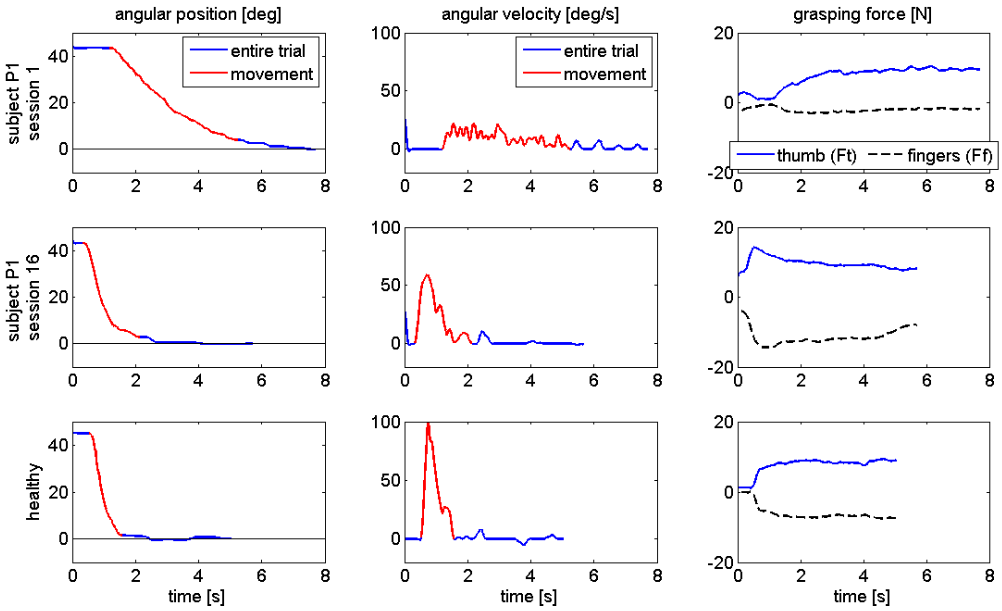

Figure 5.3: Evolution of angular position, angular velocity and grasping forces during a pronation movement for subject P1. The duration of the movement as well as the oscillations around the target decrease, while the coordination between forces applied by thumb and fingers improves (adapted from Lambercy et al., iCREATe, 2008).

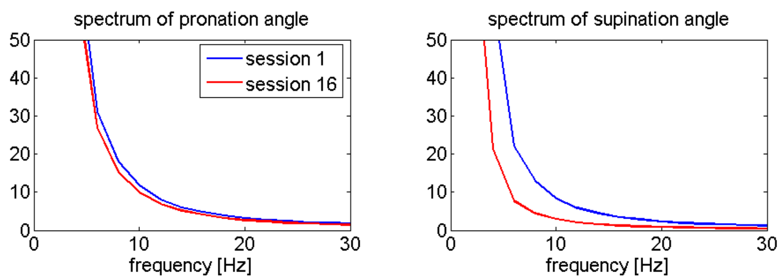

Figure 5.4: FFT spectrum of rotation angle for pronation and supination movements. The average of the trials of the first session is shown in blue and the last session in red (blue and red curves overlap on the top figure) (adapted from Lambercy et al., iCREATe, 2008).

from the CG. Results for the two post-stroke subjects are listed in Table 5.3, and can be summarized as follows:

- the two subjects were able to complete the task, i.e. to meet its accuracy constraint. A decrease in the time required to perform the twisting movement was observed in both subjects for supination and pronation. However, even after the training, the movement

Table 5.3: Results of pronation and supination movements for post-stroke subjects P1 and P3 (mean value for each session) and for a control group CG (mean of two healthy subjects). Improvements in bold correspond to the expectations.

parameter	P1 session 1	session 16	P3 session1	session 16	mean variation	CG mean of 2
pronation:						
t_m $[s]$	3.72	2.90	3.62	3.50	**-0.47 (-13%)**	2.50
$n0$ $[1/s]$	6.99	6.38	7.41	8.25	+0.12 (+2%)	6.46
t_{out} $[s]$	5.22	1.94	5.80	$*$1.89	**-3.60 (-65%)**	2.20
n_c	6.07	$*$1.93	6.69	$*$2.87	**-3.98 (-62%)**	4.25
supination:						
t_m $[s]$	5.61	4.42	4.88	$*$3.50	**-1.29 (-24%)**	3.20
$n0$ $[1/s]$	7.73	$*$6.50	7.31	7.12	**-0.71 (-9%)**	6.99
t_{out} $[s]$	0.82	1.11	4.31	3.39	**-0.32 (-12%)**	0.47
n_c	2.38	1.55	5.47	4.40	**-0.95 (-24%)**	1.35

$*$: significant variation

was longer than for healthy subjects of the same age group.

- the number of acceleration zero crossings per unit of time during the movement decreased in 3/4 cases, but the change was small in all cases. However, high frequencies in the FFT spectrum decreased during the therapy (Fig. 5.4). Altogether, this indicates slightly smoother movements after the therapy.

- the time spent in to reaching the target window for the first time, as well as the number of crossings in and out of this target window, decreased greatly for the two subjects both in pronation and supination, indicating improved precision control.

5.3.4 Discussion

P1 and P3 improved in motion speed and precision while performing the task. The parameters chosen to quantify performance showed improvement in almost all cases between the beginning and the end of the therapy (Table 5.3).

Movement precision improved:

The number of crossings in and out of the target window decreased for both subjects (P1: -68%/-35%, P3:-57%/-20% for pronation/supination). This illustrates a significant improvement in the control of the fine movement near the target. This may also indicate a decrease in co-contraction between agonist-antagonist muscle groups during the position adjustment.

Focus on movement smoothness versus precision:

The two subjects seem to have adapted with a different focus. P1 had significant improvement in the parameters related to the quality of the movement, i.e. smoothness and movement velocity. On the other hand, P3 became more accurate in reaching the target, but motion smoothness did not change much.

These differences in focus may be due to the fixtures used during the exercise. P1 was grasping a disk with a diameter of 6 *cm*, while P3 was griping a rectangular plate, to train lateral pinch (key pinch). The lateral pinch position offers more sensitivity and is more suitable for fine manipulation, such as operating an oven control, or turning a key. Training with this type of grip may thus help focus on the precision of the movement near the target.

Similarly, grasping the disk requires better coordination between the fingers to precisely control the position, but provides more stability as all the fingers are involved in the grasp. This may explain the improvement in the speed and smoothness of the movement for this type of grasp.

Supination movement is more difficult than pronation:

The results of most of the parameters related to the movement are superior for pronation compared to supination. Typically, the time required to perform a supination movement is always greater than the time required for the pronation movement (+51% for P1 and +35% for P3 at the beginning of the therapy).

This difference may be explained by the fact that, in this exercise, supination always starts from the rest position of the forearm and goes towards the physical limit of the ROM of the forearm. Consequently, pronation may be easier as it consists of the opposite displacement, i.e. moving back to the rest position. However, no larger differences in the movement parameters between pronation and supination were found for healthy subjects. Furthermore, exaggerated flexor muscle activity in stroke subjects may increase the difficulty in controlling fine movements in supination.

However, significant improvements were found for the supination movement for the two post-stroke subjects which was the major goal of the exercise (Lambercy et al., 2008).

5.4 Force modulation and proprioception exercise

5.4.1 Objectives

The objectives of this exercise are to increase the subject's sensitivity to proprioceptive inputs and use of somatosensory information, and train the subject to regulate grasping force and coordinate the thumb with the other fingers for grasping.

The *Haptic Knob* was maintained in a fixed and comfortable position, and subjects were asked to grasp and hold the knob, applying a specific grasping force adapted to their level of impairment. The exercise was composed of two phases: (i) the achievement of the target force and (ii) the maintenance of the target force. During force achievement, subjects were asked to reach a target force level while grasping the knob, i.e. apply a force of 5 $N \pm 1$ N with the thumb on one side, and the opposite same force with the fingers on the other side of the *Haptic Knob*, and maintain it for 1 second. Visual feedback by means of two indicators displayed on the monitor, one for each side of the robot, indicated the level of force applied on the knob.

During force maintenance, subjects had to maintain the same force for a duration of 10 seconds. Visual feedback was removed and indication of the level of force applied was given to the subject by means of the torque produced by the rotational DOF of the robot (i.e.

pronation/supination torque), whose amplitude was proportional to the error in force (mean of thumb and fingers forces). When both grasping forces were inside the target force window, no torque was applied. In this phase of the exercise, subjects had to rely on proprioceptive feedback of their hand and wrist to maintain and adjust the correct level of grasping force.

5.4.2 Data analysis

Force control in a trial was evaluated by subject's capacity to generate and maintain the correct grasping force on the knob:

- achievement time t_s required to initially reach the target force window.
- number of crossing in and out of the target window while attempting to match the target force, n_{c_t} and n_{c_f}, which is a measure of the control of the grasping force and the ability of the subject to precisely generate a specific force.
- the time spent inside the target force window after matching the target force is also investigated; t_{f_t} and t_{f_f} for the thumb and fingers respectively, and t_{f_s} when both thumb and fingers were applying the correct force level.

Force coordination between the thumb and the other fingers while performing opposition was evaluated using the absolute error between the two force signals. The area of the error ϵ_f normalized over the duration of the trial time was used in the analysis of the force maintenance.

5.4.3 Results

P2 and P4 trained with the force modulation and proprioception exercise during the 2 months of therapy. Results for these two subjects are listed in Table 5.4 and can be summarized as follows:

- a significant decrease in the time to reach the target force t_s was observed for both subjects (-61% for P2 and -81% for P4), indicating a better control of the grasping force, resulting in a faster force tuning.

- the number of oscillations around the target force window before reaching the desired force level, expressed by n_{c_t} and n_{c_f}, decreased. This is specially noticeable for the thumb force, as the number of crossings significantly decreased for both subjects.
- a significant improvement during force maintenance was observed for subject P4; the percentage of the time where both the thumb and fingers applied the correct force level (t_{f_s}) increased. In addition the fingers were better coordinated as indicated by a significant decrease of ϵ_f. Figure 5.5 presents the evolution of the thumb and finger forces during the two parts of the exercise for P4. Subject P2 did not improve in force maintenance, mainly because of excessive force applied by the fingers opposing the thumb during the last session.

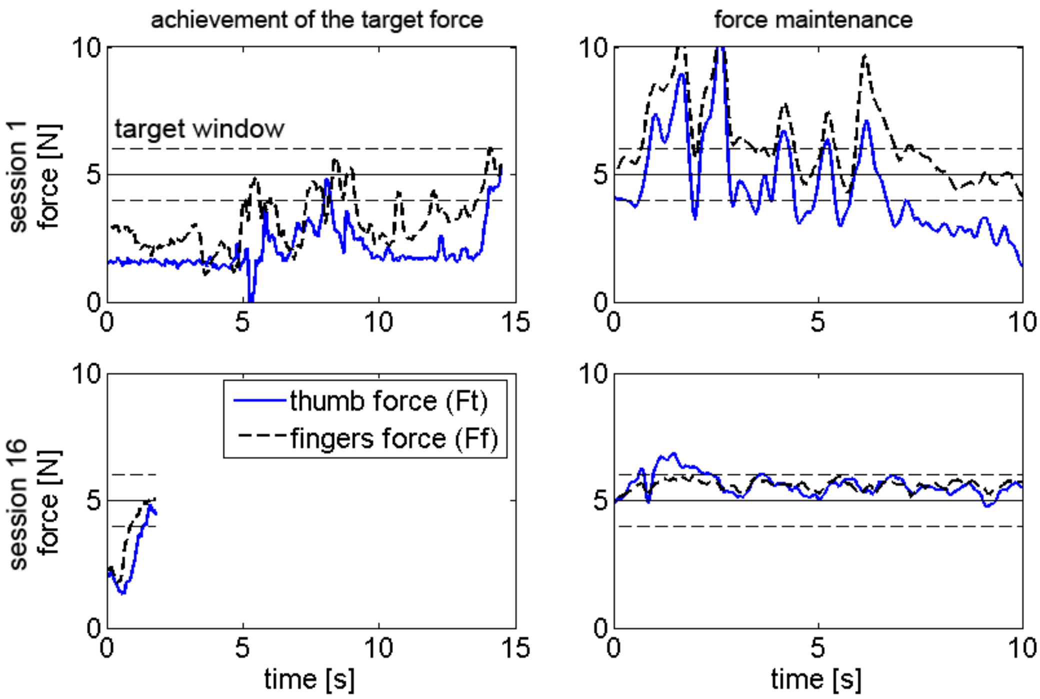

Figure 5.5: Evolution of thumb and fingers forces during achievement of the target force (left) and force maintenance (right), for one trial of the first session, and one trial of the last session for subject P4. The time required for achieving the target force and the number of oscillations around the target window decreased, while the time when correct forces were applied on the knob during force maintenance increased.

Table 5.4: Results of the force modulation and proprioception exercise for post-stroke subjects P2 and P4 (mean values for each session) and for a control group CG (mean of two healthy subjects). Improvements in bold correspond to the expectations.

	P2		P4		mean	CG
parameter	session 1	session 16	session 1	session 16	variation	mean of 2
$t_s[s]$	24.44	$*$9.43	45.65	$*$8.70	**-25.99 (-74%)**	5.12
n_{c_t}	14.24	$*$3.15	34.40	$*$7.40	**-19.05 (-78%)**	3.90
n_{c_f}	16.40	9.95	35.25	$*$6.50	**-17.65 (-68%)**	1.98
$t_{f_t}[s]$	6.77	6.27	5.05	$*$7.26	**+0.85 (+14%)**	5.60
$t_{f_f}[s]$	5.03	3.55	4.32	$*$6.55	**+0.33 (+7%)**	8.75
$t_{f_s}[s]$	4.61	3.46	3.29	$*$5.63	**+0.60 (+15%)**	5.60
$\epsilon_f[N/s]$	0.79	0.92	1.37	$*$0.62	**-0.31 (-29%)**	0.72

$*$: significant variation

5.4.4 Discussion

P2 and P4 improved their ability to generate and quickly adjust precise grasping force. The major improvements were observed during the achievement of the target force, with a higher precision in force generation and fewer oscillations around the target force. However, the time to reach the target force remained longer than for the healthy subjects.

For both subjects it was more difficult to adjust the force applied by the thumb. This illustrates the difficulties stroke survivors have in using the thumb in ADL, typically in placing it in opposition to grasp objects.

Both subjects were able to use proprioceptive feedback, progressively learning to use it to modulate grasping force and meet the accuracy constraint of the exercise. Nevertheless, the exercise was difficult for subjects to understand, because of the absence of visual feedback information to help subjects visualize the effect of their actions. Although useful to restore sensation in the impaired limb, proprioceptive feedback requires longer adaptation from subjects and is less motivating. In addition, stroke subjects with severe impairments may not be able to rely on proprioception only, and additional cues should be provided, for example audio feedback.

5.5 Subjects reports

The robot-assisted training resulted in direct benefits in ADL for the four subjects, and in a reduction of their impairments, as measured by the CMMII.

In his final interview at the completion of the study, subject P1 reported several functional improvements: he felt more secure while grasping objects with his impaired hand, and he was able to grip and hold small objects which was impossible for him prior to the therapy. Further, P1 noticed improvement in tasks involving forearm pronation/supination, such as pouring water into a glass, which confirmed the results observed with the *Haptic Knob*. Similarly, tasks such as turning a light switch on/off, or washing dishes with utensils were easier for him. In the CMMII, a decrease of subject's impairment was observed after the therapy, as P1 completed stage 4 (initially stage 3+).

P2 reported improved grasping and pinching function. He felt that his impaired limb was stronger, and could use it to carry heavy objects such as grocery bags. A decrease in upper limb impairments was observed as P2 completed stage 6 of the CMMII (initially 5+).

At the end of the therapy, subject P3 reported feeling more secure while grasping and carrying objects with her impaired hand. She also noticed improvement while pouring water into a glass, or drinking from a cup. P3 also reported improvements in the quality of her handwriting (Marinelly, August 03, 2007). An important decrease in impairment was observed, as P3 could complete stage 5 of the CMMII (initially stage 3++).

P4 also reported improvement of hand function, typically while grasping and carrying objects. He mentioned using his impaired hand more often than before the therapy, involving it in ADL such as using a key, or cutting food. An important decrease in subject's impairment was also observed; P4 completed stage 6 of the CMMII (initially stage 4++).

5.6 Discussion

The goal of this pilot study was to demonstrate the potential of the *Haptic Knob*, and our other robotic devices, as rehabilitation tools after stroke. Four chronic stroke subjects participated to this study, receiving 2 one-hour sessions of training per week during 2 months. Training was personalized to each subject and was composed of exercises with the *Haptic Knob*, the *HandCARE* and the *Delta Workstation*, to provide training for different functions of the impaired limb.

Results of the pilot study illustrated that stroke subjects responded positively to the therapy with the *Haptic Knob*; they were able to use the robot and enjoyed the interactive therapy. Subjects improved their performance in the exercises, improving grasping, forearm pronation/supination and force control. A reduction in impairments was indicated by the CMMII for every subject. Moreover, subjects reported functional improvement in daily activities at home resulting from the robot-assisted therapy. Most importantly, they regained trust in their impaired limb and started to involve it in ADL at home.

Although this study showed promising results, it presents several limitations:

- only 4 stroke subjects participated to this pilot study. This number may be enough to test the devices and verify how subjects interact with robotic systems, which was the primary goal of this study. However, it is not sufficient to statistically validate benefits resulting from the therapy.

- this pilot study was composed of exercises with three robotic devices, the *Haptic Knob*, the *HandCARE*, and the *Delta Workstation.* This provided subjects with rehabilitation at different levels of the upper limb and personalizable therapy. The disadvantage of such approach is that each subject trained with a different combination of exercises; it is thus not possible to directly compare results between subjects. Even if each robot specifically trained different tasks, it is not possible to isolate the effect of each robot, and functional improvements should be attributed to the combination of exercises. Further, therapy sessions with stroke subjects have to be limited to about one hour; extended training is less efficient as post-stroke subjects can not concentrate for a longer time, and rapidly get physically and mentally tired when exercising with their impaired limb. This time constraint and the motivation to use the three robots limited the intensity of treatment with each exercise. Indeed, subjects only trained about 15 minutes per session with each robot, which may not be sufficient to produce significant improvements.

- the CMMII assesses the overall level of arm impairment of subjects. For more precise information on the effects of therapy, additional clinical assessments should be performed on stroke subjects to monitor improvements in functional activity and in specific impairments such as limitation in ROM and spasticity.

To conclude, positive and encouraging results have been obtained with the pilot study, however a larger clinical study is required in order to validate the effects of therapy with the robotic devices.

Chapter 6

Clinical Study with the *Haptic Knob*

To evaluate the effect of robot-assisted therapy using only the *Haptic Knob*, a clinical study has been performed at Tan Tock Seng Hospital (TTSH), the largest neurorehabilitaion center in Singapore. In comparison to the pilot study presented in Chapter 5, this clinical study involved a larger number of chronic post-stroke subjects and was performed in a more systematic way, each participant training the same two exercises with the *Haptic Knob*. The therapy was composed of the *opening/closing exercise* and the *pronation/supination exercise*, which were modified from the pilot study to increase the motivation of subjects and insure proper training for each exercise. The feedback given to subjects was improved, and exercises presented as challenging games with increasing levels of difficulty. Moreover, training intensity was increased, with three sessions of robot-assisted therapy per week for six weeks.

This Chapter first presents the protocol of the clinical study, and describes the two exercises composing the therapy with the *Haptic Knob*. Results of data collected with the robot, and of clinical assessments are then presented and analyzed to illustrate the effects of the proposed robot-assisted therapy.

6.1 Methods

6.1.1 Subjects

Nine subjects (59.44±12.34 years, 4 males and 5 females) at the chronic post-stroke stage, 3 right and 6 left hemiparetic, participated in this study. Each subject gave informed consent in accordance with the Tan Tock Seng Hospital Institutional Review Board (IRB). Participants were eligible for the study if they were between 21 and 85 years of age, in the chronic stage at least 9 months after a stroke, suffered from impaired hand opening, not more than level 2 spasticity measured by the Modified Ashworth Scale ([0-5], with 0 being normal), not more than 4/5 motricity score for finger extension, but more than 3/5 motricity for shoulder abduction and elbow flexion. Subjects presenting any other neurological disorders such as ataxia, dystonia or tremor, severe pain, aphasia or visual impairment were excluded from the study. The subjects' data are summarized in Table 6.1.

Table 6.1: Baseline information for subjects participating to the clinical study.

subject	gender	age	months post-stroke	affected hand	FMA initial	MAS initial
A1	M	48	11	right (d)	13	0
A2	M	46	23	left	34	4
A3	M	55	32	right (d)	32	3
A4	F	61	16	left	43	12
A5	M	68	36	left	34	4
A6	F	78	14	left	16	1
A7	F	63	32	left	42	6
A8	F	73	9	right (d)	27	1
A9	F	43	15	left	37	6
mean±std	-	59.44±12.34	20.89±10.15	-	30.89±10.52	4.11±3.66

d: dominant hand
FMA: Fugl-Meyer Assessment [0-66]
MAS: Motor Assessment Scale [0-18]

6.1.2 Experiment conditions

Subjects trained with the *Haptic Knob* described in Section 3.5. A disk with a diameter of 6 *cm* was mounted at the output of the robot. Subjects sat in an upright position, placed the forearm on the support and grasped the *Haptic Knob* with the hand. The arm support and the height of the table on which the robot was placed were adjusted to offer the subject a comfortable position, with the shoulder abducted about 40° and the elbow flexed about 90°. If the subject had difficulty holding the knob, his/her fingers and thumb were strapped on the *Haptic Knob* with Velcro® bands. Moreover, the distal interphalangeal joint (DIP) of the thumb was taped to strengthen the joint and prevent it from slipping from the knob. Motivating therapeutic games were shown on the monitor placed in front of the subject, which indicated the task and provided feedback necessary to complete it.

Prior to the first session of therapy, a 10 minute preliminary session was performed for each potential participant, to verify that he/she was able to position his/her hand on the robot in order to perform the exercise. The ROM of the subject on the robot as well as the maximal force the subject could apply were measured. These parameters were used to personalize the therapy and adapt the initial level of difficulty of the exercise, i.e. the resistive force applied by the robot during movements and the reference position of the robot.

6.1.3 Protocol

Each subject performed two exercises inspired by ADL, similar to the exercises of the pilot study presented in Chapter 5 : (i) *opening/closing exercise*, training extension then flexion of the fingers to simulate grasping of an object, (ii) *pronation/supination exercise*, training forearm rotation, and the coordination between grasping and turning required to manipulate knobs.

Subjects participated in a one-hour training session on Monday, Wednesday and Friday for 6 weeks, i.e. altogether 18 sessions. Each session started with 15 minutes of muscle stretching followed by 20 minutes of training with the opening/closing exercise, a 5 minute break to relax and stretch the muscles, then another 20 minutes with the pronation/supination exercise. For both exercises, one training session involved 5 sets of 10 trials, with 1 minute rest between consecutive sets (Fig. 6.1).

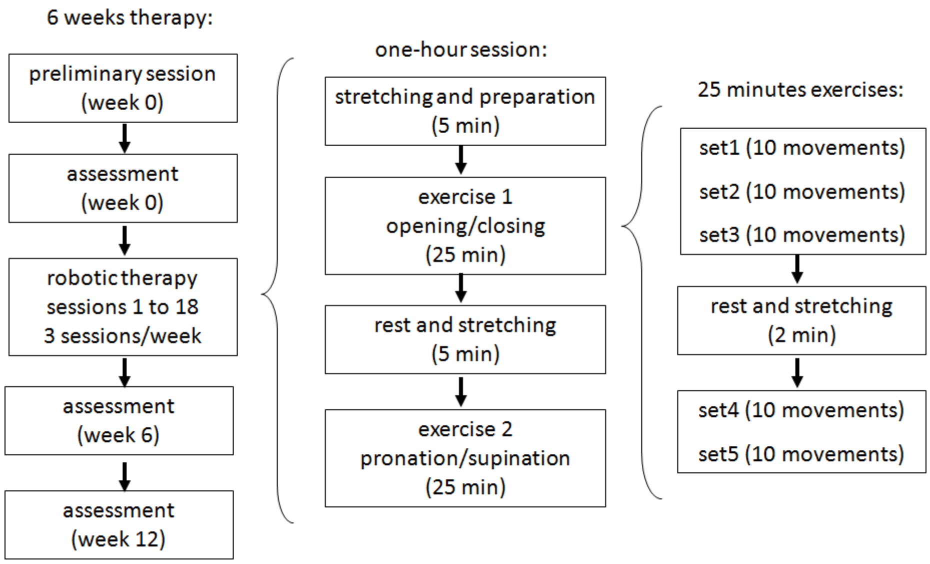

Figure 6.1: Experimental protocol of the clinical study with the *Haptic Knob*.

6.1.4 Opening/closing exercise

Because of spasticity, stroke subjects often have the hand locked in a closed position, and have problems opening it. Also, smooth grasping of objects is often difficult to control. The opening/closing exercise focuses on training these functions. The opening/closing exercise is composed of three phases; passive finger extension to open the hand (i.e., the robot opens the subject's hand while the subject can relax), a rest period between opening and closing, and an active flexion of the fingers generated and controlled by the subject.

During the passive phase, the robot opens the fingers to an extended position adapted to the subject's ROM determined in the preliminary session, which was between 10 and 15 *cm* from the tip of the thumb to the tip of the opposing fingers for the subjects of this study. At the end of the opening phase, the position was maintained by the robot for three seconds, indicated by three consecutive audio signals and a simultaneous blinking LED on the monitor. A fourth audio signal, of different pitch, indicated the beginning of the closing phase, which required the subject to actively flex the fingers against the robot. Subjects were asked to relax and to apply minimal grasping force during the opening and the three-second rest periods.

Previous experiments and results of the pilot study illustrated that stroke subjects often have trouble tuning the force applied by the fingers, and thus tend to apply inappropriate forces when asked to grasp an object (Dovat et al., 2008a). In daily activities, this may typically cause difficulties in manipulating fragile objects. In case of the *Haptic Knob*, subjects tend to close the hand quickly without controlling the movement. To train slow movements, subjects were asked to control the velocity of the hand closing movement by following a Reference Position Profile (RPP). A position indicator representing the RPP and a cursor representing the Actual Position (AP) were displayed on the left side of the monitor from top to bottom (Fig. 6.2).

The RPP is a fifth order polynomial defining a minimum jerk movement between the open and closed positions, such as natural movements tend to follow (Krylow and Rymer, 1997). The RPP amplitude was set to match the subject's ROM, and the RPP maximal velocity was based on observation of several trials without any velocity constraint.

After each trial a score

$$S_1 = 100 - a_1 \cdot \epsilon_p - a_2 \cdot n_0^2 \tag{6.1}$$

was computed based on the mean error ϵ_p between the RPP and the actual trajectory and motion smoothness. Smoothness was estimated from the number of zero crossings of the acceleration n_0 (indicating putative velocity submotions (Burdet and Milner, 1998)), normalized by the duration of the closing movement. Acceleration was numerically derived from the position signal and lowpass filtered at 10 Hz using a 2^{nd} order Butterworth filter. a_1=15 and a_2=0.5 were empirically chosen with healthy and post-stroke subjects in order to obtain a score function that is representative of the movement quality. Squaring n_0 increases the sensitivity of this parameter compared to ϵ_p. A maximal time of 10 seconds was given to the subject to

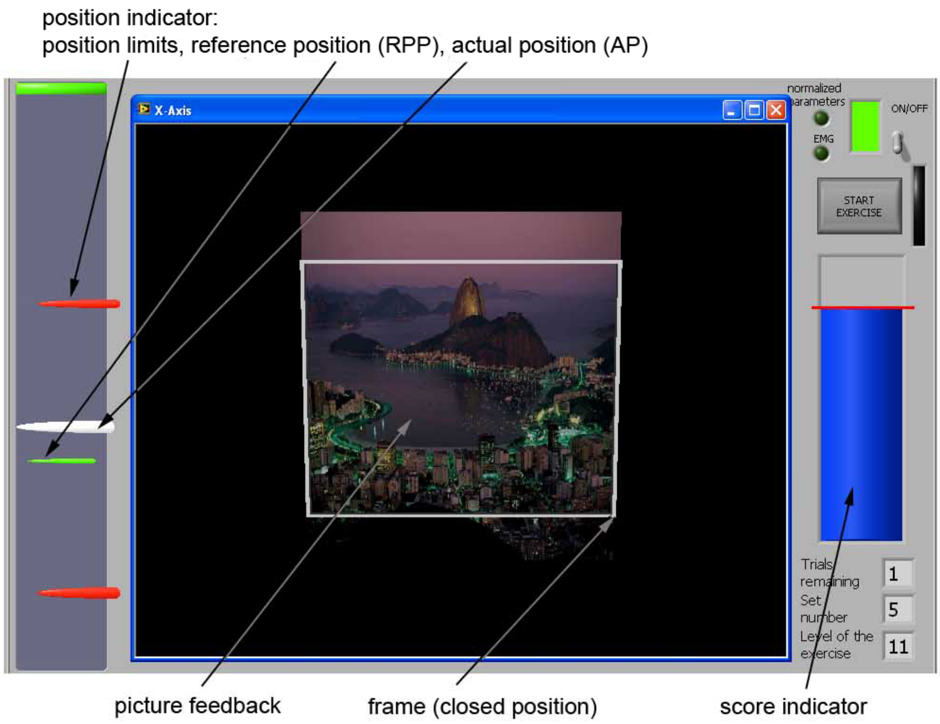

Figure 6.2: Graphical User Interface (GUI) for the opening/closing exercise, implemented in Labview8.2. The user has to reduce the size of the image to the target white frame by closing the hand. To do so, the user uses the left bar in the GUI and has to track the (green) reference position between the (red) movement start and end on the left bar with the (white) cursor. A successful movement will increase the blue indicator on the right, which represents the cumulative score on the current set. When the red line is reached, one level is completed and the subject can proceed to the next difficulty level for this exercise.

close the hand. When this limit was passed, the trial was considered as a failure, i.e. S_1=0, and the robot completes the movement.

In addition to the score and the position indicator, an attractive picture, whose size is linearly modulated with the opening of the hand, is displayed on the monitor to increase motivation. The task is successfully completed when the picture is correctly aligned with a frame representing the closed position (Fig. 6.2).

Several parameters were used to quantify the performance during each of the three parts of a trial:

- the mean absolute error ϵ_p between the reference position profile and the position waveform during closing.

- motion smoothness parameter n_0.

- the number of failed trials n_f. A trial was considered a failure if the subject was not able to reach the closed position within 10 seconds or if the trial was aborted.

- the mean force applied by the thumb and opposing fingers during the different parts of a trial: (i) the resistive force applied during the opening by the thumb F_{ot} and the opposing fingers F_{of}, (ii) the resistive force applied during the rest period between the movements F_{rt} and F_{rf}, and (iii) the grasping force applied during the closing movement F_{ct} and F_{cf}. To evaluate the coordination between the thumb and the opposing fingers during the closing movement where the subject actively grasped the robot, the mean absolute error ϵ_f between F_{ct} and F_{cf} was calculated.

6.1.5 Pronation/supination exercise

In this exercise, subjects are asked to supinate (turn so that the palm of the hand faces up) or pronate (turn so that the palm of the hand faces down) the forearm towards a specific target orientation, while the linear DOF of the *Haptic Knob* remains in the closed position. The task requires the subjects to produce accurate twisting movements and reach the target in minimum time.

The target consisted of a $\pm1°$ position window, in which the subject had to remain for 2 consecutive seconds. This window was adapted to the human discrimination threshold in orientation, which is between $0.4-1°$ (Vasquez et al., 2000). The amplitude of forearm rotation was selected between 25° and 45°, corresponding to the subjects' ROM. The initial orientation of the knob, i.e. the initial forearm orientation, was also selected for each subject to match the ROM in both supination and pronation. In addition, a resistive torque load adapted to the level of impairment of the subject was applied by the robot during the exercise in order to require him or her to hold the knob firmly during the movement.

For each trial a score

$$S_2 = 100 - b_1 \cdot \Gamma_1 - b_2 \cdot \Gamma_2 \,, \tag{6.2}$$

with $\Gamma_1 = \max\{t_m - 3, 0\}$ and $\Gamma_2 = \max\{t_T - 2, 0\}$ was computed based on the time t_m required to reach the target window, and the time t_T spent in completing the task after reaching the target window. Based on previous experiments (Lambercy et al., 2007b, 2008), the typical time required to reach the target was 3 seconds, while ideally the time spent in the target is 2 seconds. b_1=10 and b_2=7.5 were empirically chosen with healthy and post-stroke subjects in order to obtain a score function that is representative of the quality of the task. A time of 15 seconds was given to the subject to reach the target position, after which the trial was considered a failure, i.e. S_2=0, and the robot completed the movement. In this case the subject was encouraged to not resist the twisting motion of the robot.

To increase motivation, an attractive picture was displayed whose orientation and brightness were modulated linearly with the angular displacement of the hand (Fig. 6.3). When the task is successfully completed the picture is correctly aligned with a frame representing the target, which is rewarded by maximum brightness and a target indicator displayed at the bottom of the picture. Visual feedback of the knob orientation was amplified by a factor of 2 to increase the sensitivity.

The following parameters were computed to analyze the performance:

- the number of failed trials n_f, i.e. if the subject did not succeed in reaching and maintaining the target orientation for 2 seconds during the 15 seconds allowed for the task. The number of failed reaching movements n_r, i.e. when the subject did not reach the target window at all, was also considered.

- the movement duration t_m, where movement onset and end were determined from the angular velocity threshold 0.02·median$\{\omega_{max,i},\ i = 1 \ldots M\}$, where $\omega_{max,i}$ is the maximal angular velocity of the i^{th} trial, and M the total trials number.

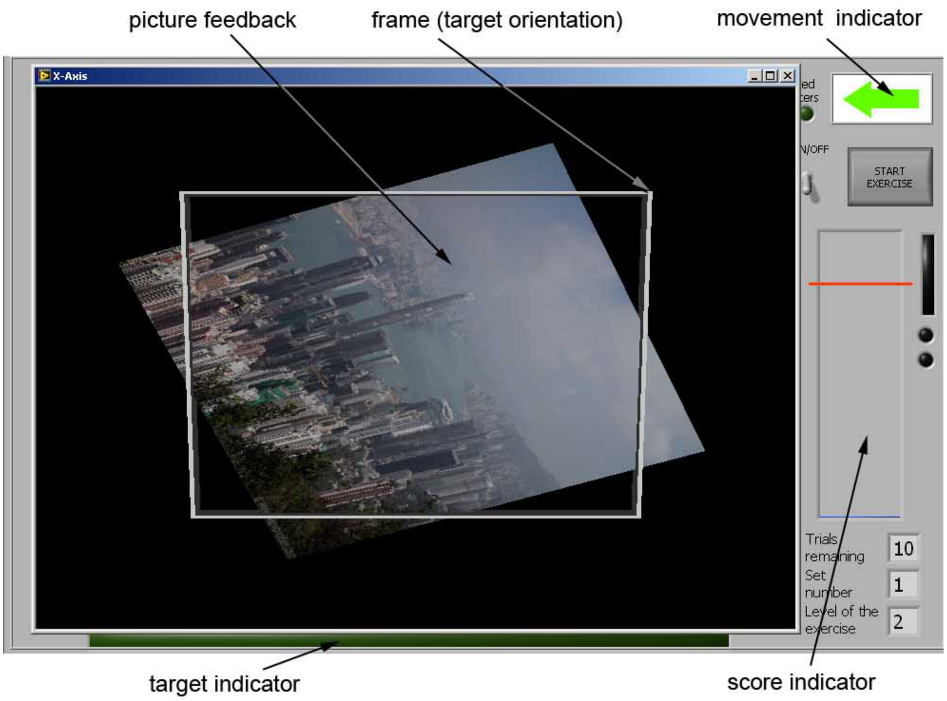

Figure 6.3: GUI for the pronation/supination exercise, implemented in Labview8.2. The user has to turn the image in the direction indicated by the green arrow at the top right corner into the frame, and to align it with the white frame representing the target orientation. The cumulative score is indicated on the right.

- as a motion smoothness measure, the number of zero crossings of the angular acceleration normalized by the movement duration, denoted n_0.
- the time t_T to adjust the angular position once the target was reached for the first time.
- the number n_c of crossings in and out of the target window indicating oscillations around the target window. Ideally this parameter should be 1, i.e. the subject did not leave the target window once it was entered.

If a trial was a failure, t_m and t_T were set to 15 seconds, i.e. the maximal time given for one trial.

6.1.6 Adaptable task difficulty

The two exercises are presented as games with increasing levels of difficulty that the subject has to complete one after the other. Each level corresponds to an incremental increase in the resistive force or torque applied by the robot during motion or a variation of the exercise parameters. In the opening/closing exercise, the velocity of the RPP is modified, slower movements requiring fine control being considered as more difficult. For the pronation/supination exercise, the size of the target window is progressively reduced, thus requiring more precise positioning. Table 6.2 summarizes the evolution of the parameters of each exercise as a function of the difficulty level. In a first step, the resistive force or torque is increased to strengthen arm and hand muscles. In a second step, movement duration or required accuracy is modulated to train hand control or precision, respectively. The last three levels of difficulty of the opening/closing exercise use variable parameters in order to force subjects to adapt to different conditions and apply suitable grasping force. In level 10 and 11, the resistive force and movement duration can take two different values, which are switched after each trial. In the last level, parameters are randomly selected within the range of values where the exercise is feasible for the subject. A similar strategy could not be used for the pronation/supination exercise, as random resistive torque level was found to be too difficult for stroke subjects to overcome.

For both exercises, scores in individual trials are summed at the end of each set (10 repetitions). If the total score is higher than 700, the subject can proceed to the next difficulty level. However only one level can be completed per session to ensure that the subjects train for a sufficient amount of time at each difficulty level. Figure 6.4 shows two chronic stroke subjects during training.

To estimate performance and compare the results between subjects, the first and last sessions of therapy used the same *evaluation parameters*. These parameters, shown in Table 6.3, were determined in preliminary tests with healthy and stroke subjects, and correspond to a medium difficulty level. The last two sets of sessions 4, 8, 12, and 16 also used the

Table 6.2: Exercise parameters for each difficulty level. F_{test} and τ_{test} are defined during the preliminary session where the subject tries the robot.

	Opening/closing exercise		Pronation/supination exercise	
level	resistive force [N]	closing duration [s]	resistive torque	accuracy [deg]
1	0.2 F_{test}	3	0.0 τ_{test}	[-1, 1]
2	0.4 F_{test}	3	0.2 τ_{test}	[-1, 1]
3	0.6 F_{test}	3	0.4 τ_{test}	[-1, 1]
4	0.8 F_{test}	3	0.4 τ_{test}	[-0.5, 0.5]
5	0.8 F_{test}	6	0.6 τ_{test}	[-0.5, 0.5]
6	1.0 F_{test}	3	0.8 τ_{test}	[-0.5, 0.5]
7	1.0 F_{test}	6	0.8 τ_{test}	[-0.3, 0.3]
8	1.2 F_{test}	3	1.0 τ_{test}	[-0.3, 0.3]
9	1.4 F_{test}	3	1.2 τ_{test}	[-0.3, 0.3]
10	0.5 F_{test} or 1.0 F_{test}	3 or 6	1.2 τ_{test}	[-0.2, 0.2]
11	0.5 F_{test} or 1.0 F_{test}	3 or 6		
12	random in {0,40}	random in {3,6}		

F_{test}: maximum voluntary grasping force (maximum value = 30 N)
τ_{test}: resistive pronation/supination torque subjects must overcome (maximum value = 250 mNm)

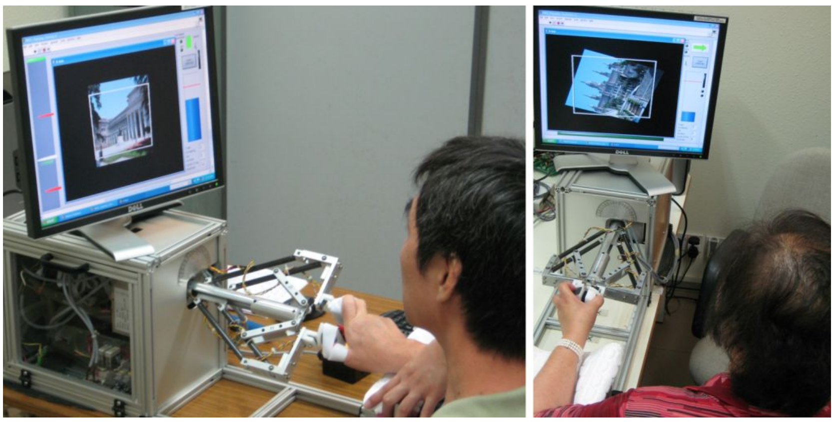

Figure 6.4: Stroke subjects training with the *Haptic Knob* at TTSH rehabilitation center.

evaluation parameters to track the evolution of subjects' performance during the therapy. In both experiments, differences in parameters between the successful trials of the first and last sessions were analyzed using a Student's t-test with 95% confidence level.

Table 6.3: Evaluation parameters.

Opening/closing		Pronation/supination	
opening range	6 *cm**	rotation range	25 *deg*
resistive force	20 *N*	resistive torque	50 *mNm*
closing duration	5 *sec*	accuracy	±0.5 *deg*

* we normally used 6 to 12 cm of hand opening by using a suitable knob.

6.1.7 Functional assessments

Subjects underwent functional motor assessment three times during the therapy; prior to the beginning (week 0), at the completion of the therapy (week 6), and 6 weeks after the end (week 12) to investigate the retention. All assessments were done by a single blinded occupational therapist and include:

- Fugl-Meyer arm motor scale (FMA, range [0-66]) (Fugl-Meyer et al., 1975). The FMA is a performance-based impairment index commonly used in research studies. It is composed of 33 tasks, with 21 involving upper arm and joint coordination, and 12 involving wrist and hand activities. Each task is graded 0, 1 or 2, with 2 corresponding to a normal motor performance.

- Motor Assessment Scale (MAS, range [0-18]) (Carr et al., 1985). The MAS is based on a task-oriented approach, and assesses functional tasks rather than isolated patterns of movements. It is composed of 3 parts corresponding to upper arm function, hand movements, and advanced hand activities. Each part consists in 6 consecutive activities of increasing difficulty. The score for each part corresponds to the last activity properly completed by the subject.

- Dynamometer recording of grip strength. The grip strength is measured 3 times for each hand using a digital grip dynamometer (Dynex® Hand Dynamometer, DyNex−1).

- Nine hole peg test (NHPT) (Grice et al., 2003). This assessment is used to evaluate finger dexterity. Subjects have to position 9 pegs in nine holes, using one hand only, in a maximal time of 50 seconds. The number of pegs placed per second is used to evaluate the performance. Measurements are repeated 3 times for each hand.

- Hong Kong Functional Test of Hemiparetic Upper Extremity (FTHUE, range[0-7]) (Wilson et al., 1984). The Hong Kong version of the FTHUE has 7 stages composed of tasks corresponding to typical ADL involving the hand, such as drinking from a glass or turning a key. In order to complete a stage of the assessment, the subject should be able to perform all the tasks of the stage.

Secondary outcomes were measured using the Motricity Index for affected upper limb (range [0-100]) Demeurisse et al. (1980), the Modified Ashworth scale for spasticity of shoulder abductors, elbow, wrist and finger flexors (range [0-5]) (Bohannon and Smith, 1987). Pain and fatigue were assessed using a visual analogue scale after each session, and a subjective score of satisfaction (1,2,3 or 4) was given by the subject at the end of the therapy.

6.2 Results

6.2.1 Opening/closing exercise

Table 6.4 summarizes the results of the opening/closing exercise during the first and last sessions of the therapy. Detailed results for each subject can be found in the Table A.1 of the Appendix.

Task performance

All subjects were able to perform the required task and showed gradual progress in the opening and closing exercise, and eventually became able to perform the exercise at the maximal level of difficulty by the end of the therapy. The score of the exercise, based on both movement control and smoothness (see Section 6.1.4), also significantly improved during the therapy for all the subjects, as both parameters decreased (Table 6.4).

Table 6.4: Mean ± standard deviation of the parameters of the opening/closing exercise, for the 9 post-stroke subjects, in the first and last sessions of therapy.

parameter	session 1 (week 0)	session 18 (week 6)	modification	p-value
n_f	11.67±14.31	0.44±0.88	-11.22±13.81 (-96%)	<0.001
ϵ_p [cm]	0.83±0.41	0.42±0.21	-0.41±0.31 (-50%)	<0.001
n_0 [1/s]	6.15±0.57	5.71±0.52	-0.44±0.52 (-7%)	<0.05
S_1	63.54±21.14	83.77±7.94	+20.23±14.90 (+32%)	<0.05
F_{ot} [N]	6.02±4.77	6.20±4.20	+0.18±2.81 (+3%)	0.09
F_{of} [N]	8.83±4.64	9.20±3.75	+0.37±3.03 (+4%)	0.13
F_{ct} [N]	8.23±4.19	8.48±2.14	+0.25±3.22 (+3%)	0.09
F_{cf} [N]	11.60±2.75	12.00±2.80	+0.40±3.45 (+3%)	0.25
F_{rt} [N]	9.57±6.31	10.61±4.93	+1.04±3.83 (+11%)	0.08
F_{rf} [N]	12.21±5.77	12.33±3.85	+0.12±3.61 (+1%)	0.18
$\epsilon_f [N]$	5.02±3.84	4.57±2.74	-0.45±2.82 (-9%)	0.43

Motion performance

Figure 6.5 illustrates the evolution of position waveforms in closing movements for subject A2. We see that this subject becomes progressively better able to move along the desired trajectory. In the first session some trials were not completed, but this disappeared in later sessions. These trends were confirmed in all subjects. The number of failed trials, as well as the mean absolute difference ϵ_p between the actual position waveform and the reference position profile, significantly decreased between the first and the last sessions of therapy, both with p <0.001.

At the end of the training, it was easier for subjects to follow the RPP and they reached the closed position on time. All subjects but A1 and A6 completed all the trials of the last session successfully. A1 still failed in several trials of the last session, however this subject's performance was particularly bad during the last session. A6 showed a significant improvement and was able to perform 48 of the 50 closing movements as compared to the first session where only 6 movements could be completed.

The mean number of acceleration zero crossings during the movement n_0 decreased for most of the subjects (p <0.05), but the change was small in all cases, indicating slightly

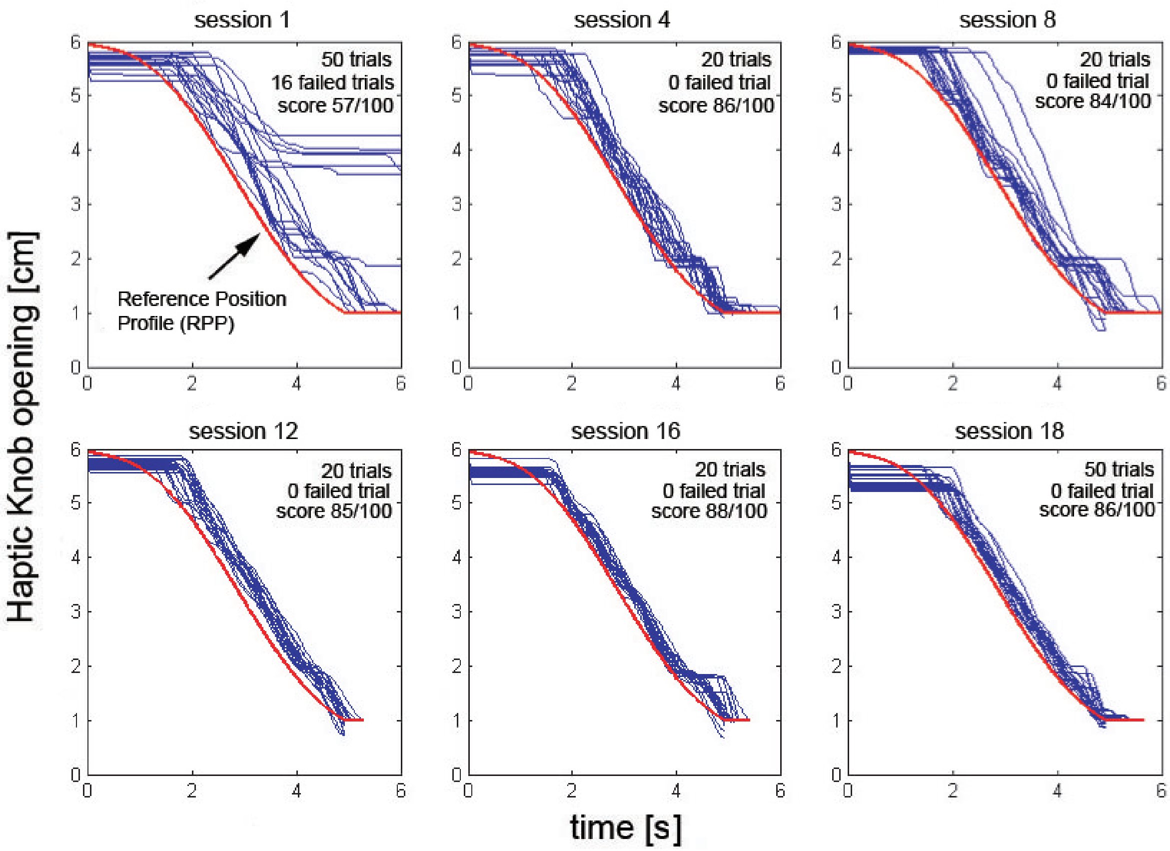

Figure 6.5: Position waveform for trials of subject A2 using evaluation parameters defined in Table 6.3. The thick line represents the reference position profile to follow.

smoother movements after the therapy. n_0 increased for A4 and A7, however, these subjects already made quite smooth closing movements at the beginning of the therapy.

Force control

Figure 6.6 shows the force profiles of three representative subjects in one trial of session 4. The three different parts of the trial can clearly be identified. The force applied by the subject linearly increases during opening, as muscle tone resists the opening. The force decreases slightly during the rest period as the muscles relax. During the closing, subjects generate force to close the knob while the robot applies a constant 20 N load.

The evolution of force parameters varied among subjects as a function of their hand im-

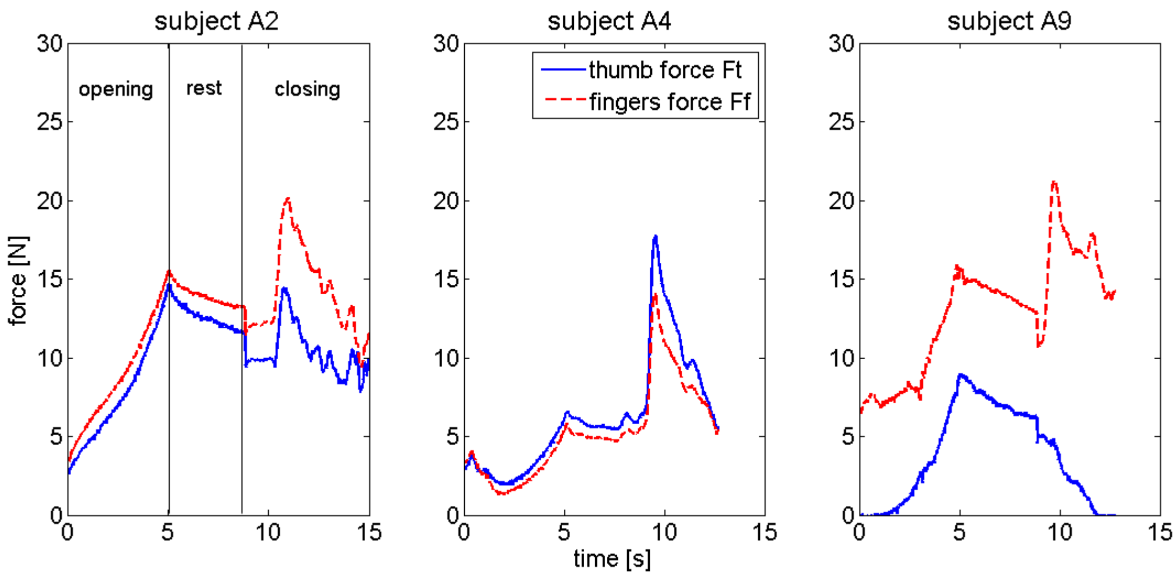

Figure 6.6: Thumb force (dashed) and opposing fingers force (plain) applied during opening/closing trials of session 4 for three subjects with different level impairments: high muscle tone (A2), moderate muscle tone (A4) and muscle weakness (A9).

pairment. Subjects A1, A2, A3 and A5 suffered from high muscle tone in finger and thumb flexors. Initially, these subjects exerted high forces on the knob during each part of the trial, as illustrated in Figure 6.6 for A2 (graded 2 and 3 on the Modified Ashworth scale for thumb and finger spasticity, respectively). The total force (addition of thumb force and finger force) applied on the robot during opening and rest was higher than the required 20 N, which explains the initial drop in position and force often observed at the beginning of the closing part. During the therapy, these subjects decreased the resistive force applied on the knob during opening and rest, suggesting a more relaxed posture, and a decrease of finger and thumb spasticity as a result of repetitive passive extension. In order to control the closing movement and reach the 20 N required to close the knob, A1, A2 and A3 decreased the grasping force F_{ct} and F_{cf} during closing movement, while A5 achieved a better balance between the thumb and the opposing fingers, i.e. ϵ_f decreased significantly (p <0.01), such that similar forces were applied by thumb and opposing fingers during the closing movement at the end of the therapy.

Subject A4 had minimal muscle tone (i.e. 0 on the Modified Ashworth scale for both thumb and fingers spasticity) and was capable of much better force control. Typically, a small increase in the force applied on the knob during the opening phase was observed, but the force required to close the robot was clearly generated and controlled by the subject (Fig. 6.6). During therapy ϵ_f significantly decreased ($p < 0.01$) indicating a better balance between thumb and opposing fingers during grasping.

Subjects A6, A7, A8 and A9 had limited muscle tone, but suffered from muscle weakness in wrist, thumb and fingers. One trial of subject A9 (graded 0 on the Modified Ashworth scale for both thumb and fingers spasticity) is presented in Figure 6.6. The large difference in thumb and finger forces is due to the hand position. Because of initial muscle weakness, subject A9 could not properly grasp the knob, but rested her hand on the *Haptic Knob*. The higher force recorded by the upper part of the device, corresponding to the fingers, is thus caused by the weight of the hand and fingers. During opening, forces increased because of muscle stretching, the thumb resisting the opening in a similar way to other subjects. However, during the closing phase, the total force required to close the robot was generated on the fingers' side, with thumb force progressively decreasing. This illustrates that, to compensate for muscle weakness at the beginning of the therapy, subject A9 typically used the entire arm to push on the upper part of the *Haptic Knob* in order to close it, without using the thumb. During the therapy, subjects A7, A8 and A9 increased the force applied during the different parts of a trial. Subjects A6 and A9 improved the balance between the thumb and the opposing fingers during closing, while for A7 and A8 the force of opposing fingers remained higher than thumb force. However, thumb forces significantly increased for A8 and A9, indicating that these subjects started to involve the thumb in grasping. An increase of muscle strength was observed in these subjects as they were able to reach the more difficult levels of the exercise, with higher resistive forces.

Due to the differences between subjects' impairments, no significant trend was observed among subjects concerning the evolution of the parameters relative to the force. Nevertheless, each subject improved force control in his or her own way in order to improve the grasping, most subjects improving the balance between forces applied by the thumb and opposing fingers. The principal variations were observed in thumb force, which illustrates the important role of this digit in grasping tasks.

6.2.2 Pronation/supination exercise

Table 6.5 summarizes the results obtained for the pronation/supination exercise during the first and last sessions of the therapy. Detailed results for each subject can be found in the Table A.2 of the Appendix.

Table 6.5: Mean ± standard deviation of the parameters of the pronation/supination exercise, for the 9 post-stroke subjects, between the first and last sessions of therapy.

parameter	session 1 (week 0)	session 18 (week 6)	modification	p-value
n_f	23.33±18.96	11.22±15.18	-12.11±11.20 (-52%)	<0.001
n_r	14.33±16.10	4.78±8.80	-9.55±12.43 (-67%)	<0.001
t_m[s]	7.65±3.63	4.28±2.83	-3.37±2.63 (-44%)	<0.001
n_0[1/s]	6.18±0.53	5.97±0.54	-0.21±0.07 (-3%	0.16
t_T[s]	7.99±3.92	5.06±3.32	-2.93±2.27 (-37%)	<0.001
n_c	4.39±1.61	3.55±3.13	-0.84±6.37 (-19%)	0.25
S_2	32.82±24.16	63.28±32.03	+30.46±16.39 (+90%)	<0.001

Task performance

All subjects showed progress in the exercise; however, subjects A1, A3 and A6 did not complete level 1, as they could not complete enough movements in a set. The score of the exercise significantly increased for all subjects, with a mean increase of +90 %.

Several subjects had difficulty in performing the task at the beginning of the therapy; during the first session the number of failed trials n_f was very high: a mean of 23.3 out of 50. The primary reason for failure was the inability of subjects to generate movements of sufficient amplitude, both in pronation and supination. At the end of the therapy, however, the number of failed trials decreased significantly (to a mean of 11.2 failed trials), indicating a significant improvement in the execution of the twisting movement (p <0.001).

Subjects A2, A4, A5, A7, A8 and A9 were able to reach the target on all trials of the last session during both pronation and supination. During the first session, subject A3 could not perform the task due to hypertonicity in the wrist and fingers limiting his range of motion and preventing him from properly holding the knob during movements. Most of the trials (sets 2 to 5) were thus performed passively by the robot. At the end of the therapy, subject A3 was able to relax his wrist and fingers to actively perform the task during all the trials, reaching the target window and completing the task in 80% of the trials (Fig. 6.7). Subject A1 had very impaired pronation and was not able to perform any reaching movement in this direction, or fine position adjustment in the case of overshoot. A1 slightly improved supination movement during the therapy.

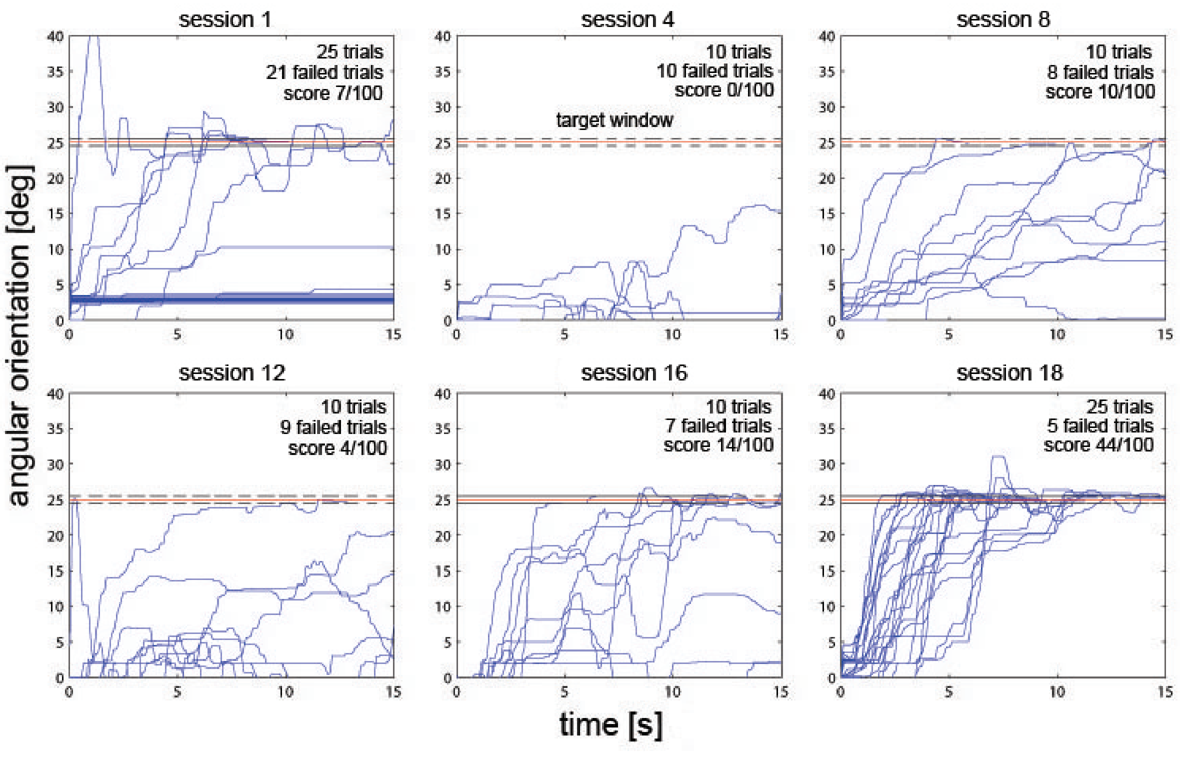

Figure 6.7: Angular position waveform of subject A3 for pronation movements when using evaluation parameters defined in Table 6.3. Note that during session 1, some trials were assisted by a physiotherapist to teach the patient the movement to perform.

Twisting movement

Twisting movements to reach the target orientation were significantly faster at the end of the therapy for all subjects; a mean decrease of -44% was observed in t_m (p <0.001). This decrease was observed in both pronation and supination movements. No significant modification of movement smoothness was observed during the therapy.

The ability to perform precise movement was evaluated by the time t_T required to complete the exercise, i.e. to remain stationary once the target was reached for the first time, and the number of crossings around the target n_c, representing oscillations. t_T decreased at p<0.001, suggesting a better ability to fine tune and maintain the target orientation. n_c decreased for all subjects except A2 and A6 where this parameter increased as these subjects were initially not able to reach the target at all. They could achieve the task at the end of the therapy, but still lacked some control of the movement when reaching the end of their ROM. A4, A7, A8 and A9 showed significant improvement in both precision parameters, approaching the ideal values for t_T and n_c, i.e. 2 and 1 respectively, indicating a significant improvement in control and precision of pronation and supination movements.

Although subjects showed improvements in both pronation and supination, results suggest larger improvements in pronation. A majority of subjects initially had more impaired pronation, but at the end of the therapy, pronation was similar or even better than supination. Pronation became more precise and orientation adjustments easier, which confirms observations of the pilot study. This may be due to initial weakness in small pronator muscles that are less involved in ADL, in contrast to supinator muscles such as the biceps. On the other hand, supination may be more difficult to precisely control because of exaggerated flexor muscle activity.

6.2.3 Functional Assessment

According to the functional assessment, a decrease in impairment was observed in all post-stroke subjects after completion of the therapy. Table 6.6 summarizes the results of the main clinical outcomes.

Subjects improved the motor function in average of 4.3 points or +14% with $p<0.001$ in the Fugl-Meyer assessment (FMA), and this increase was ≥ 5 points in 5/9 subjects, with a maximum of 11 points for A9. An increase of up to 2 points in the Motor Assessment Scale (MAS) was also observed, and a mean improvement of 11% of the grip strength of the impaired hand, normalized with the strength of the unimpaired hand, was recorded among subjects.

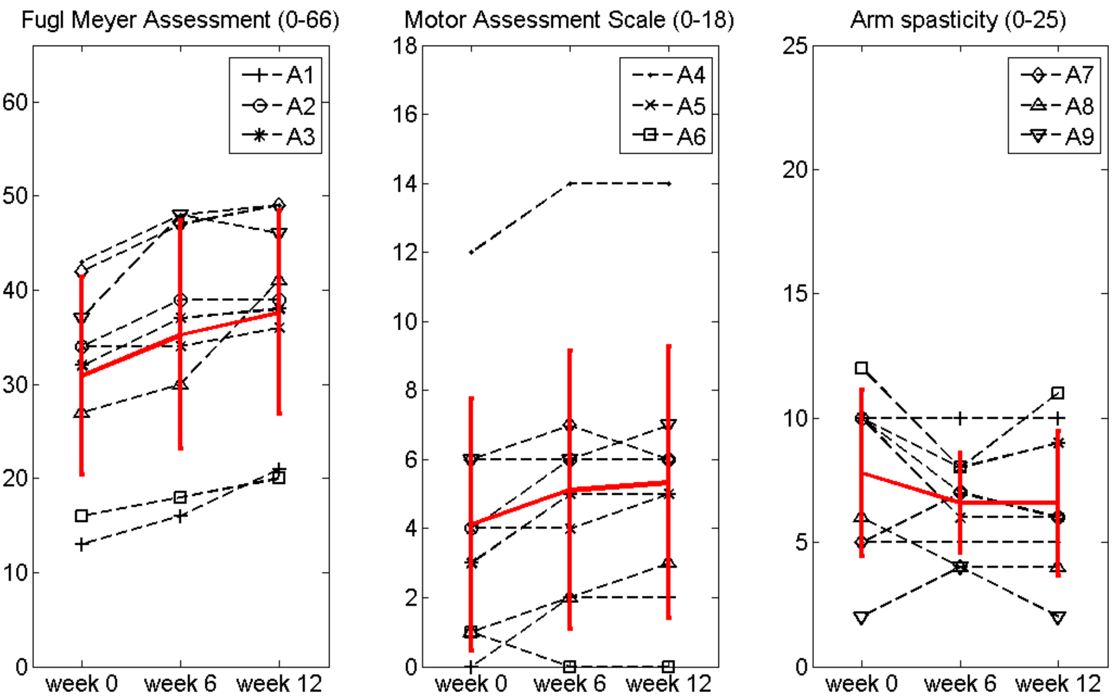

Figure 6.8: Assessments scores for the Fugl-Meyer Assessment (FMA) and the Motor Assessment Scale (MAS), and measurements of arm spasticity (Modified Ashworth scale) for the nine subjects that completed the study.

Spasticity in flexor muscles, measured by the Modified Ashworth scale, decreased at all levels of the upper limb, i.e. in shoulder abductors (-7%), in elbow (-35%), wrist (-8%), finger (-8%) and thumb flexors (-10%). Motor impairment of the arm and hand significantly decreased, as was shown by a 9% ($p<0.05$) increase of the Motricity Index.

Other clinical outcomes were not satisfactory. Before the therapy, most subjects were unable to perform the nine hole peg test with their impaired hand, compromising the use of this assessment in this study. Similarly, the requirements in performance of hand function for the Functional Test of Upper Extremity (Hong Kong version) were too high, limiting subjects to the first stages where the test is not sensitive enough to show potential evolution. Figure 6.8 summaries the evolution of FMA, MAS and arm spasticity for each subject.

Improvements obtained during training with the *Haptic Knob* were maintained 6 weeks after the completion of therapy (Table 6.6). FMA and MAS scores were similar or slightly better for the more severely impaired subjects such as A1, A6 and especially A8 who presented an additional improvement of 11 points in the FMA during the 6 weeks after the therapy. Subjects with mild impairment (i.e., FMA>30) showed only minimal improvement in FMA and MAS scores by the end of the therapy, as shown in Figure 6.9. Muscle tone remained stable for most subjects, although finger spasticity tended to slightly increase in subjects with already high spasticity such as subjects A3 and A6.

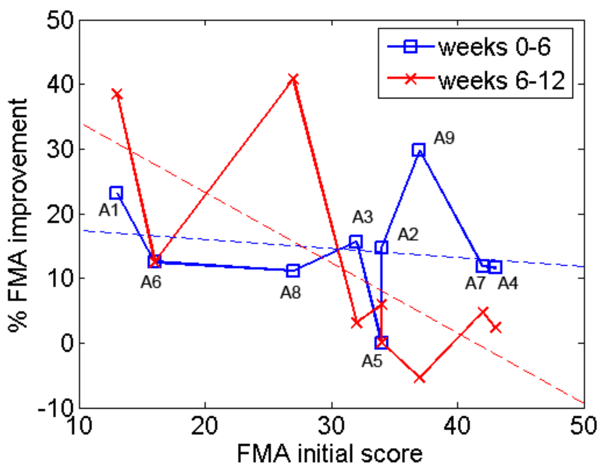

Figure 6.9: Variation of the Fugl-Meyer scores during the 6 weeks robot-assisted therapy and the 6 weeks after the therapy. Each point of the curves represents one of the stroke subjects, and dashed lines are linear fits.

The average improvements in motor function during the six weeks following the therapy were smaller than during the robot-assisted therapy as illustrated in Figure 6.8. Nevertheless, between the first (week 0) and last (week 12) assessment, a mean increase of 6.78 points or

+22% (p <0.01) in the FMA and 1.22 points or +30% (p=0.07) in the MAS was observed, together with a mean decrease of 15% (p <0.05) in arm spasticity. This illustrates that chronic stroke subjects can further improve motor skills, and that improvements observed after the robot-assisted therapy are acquired.

Table 6.6: Results of clinical assessments for 9 post-stroke subjects (mean±std).

assessment (normal score)	week 0	week 6	modification (0 to 6)	*p*-value	week 12	modification (0 to 12)	*p*-value	modification (6 to 12)	*p*−value
Fugl-Meyer Assessment (66)	30.89±10.52	35.22±12.13	+4.33±3.04 (+14%)	<0.001	37.67±10.79	+6.78±3.42 (+22%)	<0.001	+2.44±3.71 (+7%)	<0.05
wrist/hand (24)	8.56±4.50	9.78±4.79	+1.22±1.09 (+14%)	<0.05	11.11±5.35	+2.55±2.24 (+30%)	<0.001	+1.33±1.58 (+14%)	<0.01
shoulder/elbow (42)	22.33±8.06	25.44±9.25	+3.11±2.76 (+14%)	<0.001	26.56±7.75	+4.23±2.99 (+19%)	<0.01	+1.11±2.76 (+4%)	0.08
Motor Assessment Scale (18)	4.11±3.66	5.11±4.04	+1.00±1.18 (+24%)	0.10	5.33±3.94	+1.22±1.09 (+30%)	0.07	+0.22±0.67 (+4%)	0.18
Grip force (imp./unimp.)	0.23±0.16	0.26±0.15	+0.03±0.07 (+11%)	0.47	0.24±0.13	+0.01±0.15 (+6%)	0.41	-0.01±0.11 (-5%)	0.38
Motricity Index (100)	48.89±15.78	53.33±18.39	+4.44±5.29 (+9%)	<0.01	54.44±15.88	+5.56±4.69 (+11%)	<0.01	+1.11±4.48 (+2%)	0.21
Modified Ashworth scale (0)	7.78±3.35	6.56±2.01	-1.22±2.33 (-16%)	0.45	6.56±2.92	-1.22±1.79 (-15%)	<0.05	-0.00±1.41 (-0%)	0.34
shoulder abductors	1.56±1.24	1.44±1.24	-0.12±0.33 (-7%)	0.17	1.44±1.24	-0.11±0.33 (-7%)	0.17	-0.00±0.00 (-0%)	–
elbow flexors	2.22±0.83	1.44±0.73	-0.78±1.39 (-35%)	<0.05	1.44±0.73	-0.78±1.39 (-35%)	<0.05	-0.00±0.00 (-0%)	–
wrist flexors	1.44±0.73	1.33±0.50	-0.11±0.60 (-8%)	0.50	1.22±0.67	-0.22±0.67 (-15%)	0.28	-0.11±0.33 (-8%)	0.17
finger flexors	1.44±1.01	1.33±0.71	-0.11±0.78 (-8%)	0.35	1.44±0.88	-0.00±1.12 (-0%)	0.19	+0.11±0.60 (+8%)	0.22
thumb flexors	1.11±1.05	1.00±0.87	-0.11±2.33 (-10%)	0.47	1.00±0.87	-0.11±0.93 (-10%)	0.05	-0.00±0.87 (-0%)	0.38

6.3 Discussion

This work aimed at developing robot-assisted therapy to retrain hand opening/closing and forearm pronation/supination after stroke, and assess behavioral gains resulting from this intervention. Two motivating game-like exercises were implemented on the *Haptic Knob*, a 2 DOF robotic interface to train hand and forearm functions. Nine chronic post-stroke subjects participated in a 6 week therapy program composed of 18 one-hour sessions of robot-assisted training. The objectives of the therapy were to obtain functional improvement in hand activity, decrease spasticity in arm and hand flexor muscles, and to improve subject's ability to perform ADL.

After 6 weeks of therapy with the *Haptic Knob*, subjects with chronic stroke showed significant improvement in their performance with the robot, suggesting improvement in hand and forearm function. Grasping control trained by the first exercise improved during the therapy as subjects with high muscle tone improved muscle control while weaker subjects increased finger strength, especially thumb force. Forearm pronation and supination became easier to perform and more accurate. These results were confirmed by clinical outcomes. A mean increase of 24% was observed in the Motor Assessment Scale (MAS) indicating improvement in functional tasks of arm and hand. A mean increase of 14% was observed in the Fugl-Meyer Assessment (FMA), as well as a decrease of 16% in spasticity in flexor muscles of the entire arm. These results supports the hypothesis that intensive use in a repetitive training program improves motor function in chronic stroke subjects who have completed conventional training some time ago. These improvements correspond to a noticeable increase of hand and arm function of stroke survivors.

In addition to clinical assessments, participants reported improvement in their hand function after the robot assisted therapy, and stated that they were using their impaired hand more than previously. Furthermore, subjects were highly satisfied with the quality of the robot therapy, giving a mean 3.2/4 satisfaction grade, and eventually asking for additional sessions.

The observed improvements in arm and hand function were maintained 6 weeks after the completion of the therapy, suggesting long term improvement in the motor condition. At the end of the therapy, stroke subjects returned to a classical rehabilitation program, i.e. weekly physio- and occupational therapy. The plateau observed in most subjects during this period suggests that the improvement obtained during the robot-assisted therapy can be attributed to the treatment with the *Haptic Knob*.

Nevertheless, the more severely impaired subjects (FMA<30) continued to significantly improve their arm and hand motor function after the completion of robot-assisted therapy. This may be due to an increased use of the impaired limb in subjects' daily activities at home, mediated by the motor improvements obtained during the robot-assisted therapy, and the resulting gain in motivation and confidence in their motor abilities. In a recent study, Han et al. suggested the presence of a threshold of spontaneous activity in stroke rehabilitation; below the threshold, intense rehabilitation is required for motor improvement and only little progression is possible. However, once the spontaneous activity threshold is reached, subjects use their arm for daily tasks in a way that promotes further improvements in motor function, which may, in theory, lead to complete recovery (Han et al., 2008). In our study, the less severely impaired subjects showed little to no additional improvement in motor function during the 6 weeks after the therapy, which suggests that more rehabilitation therapy should be performed to obtain further improvements. Additional clinical assessments in the months following the completion of the therapy would be required to verify this hypothesis.

The results obtained in this clinical study confirm the potential of robotic devices and of the *Haptic Knob* for post-stroke rehabilitation, and are in accordance with results obtained in other robot-assisted studies on upper limb rehabilitation, where improvements of 3.0 to 7.6 points in the FMA were observed. Table 6.7 summarizes results of recent studies with chronic stroke subjects focusing on arm, wrist and hand rehabilitation, and using the FMA as outcome measure (Hesse et al., 2008; Volpe et al., 2008; Krebs et al., 2007; Nef et al., 2007; Lum et al., 2002; Fasoli et al., 2004, 2003; Takahashi et al., 2008). In addition to improvement in FMA scores, a decrease in arm muscle spasticity was also observed in most studies. Even if it is not possible to directly compare these studies as they have different objectives and protocols, it is still interesting to notice a similar trend in the evolution of FMA scores underlining the potential of robot-assisted rehabilitation.

In their study, Takahashi et al. obtained larger improvements in FMA scores. This may be explained by the higher intensity of their therapy, participants training 1.5 hour with the HWARD robot 5 days per week (Takahashi et al., 2008). Such results suggest the design of more intensive protocol of experiments for further studies (Kwakkel et al., 2006), however daily sessions may be too constraining for outpatients and therapists.

Lum et al. studied the effect of bilateral training with their MIME robot, where the movement of the unimpaired arm is mirrored to assist movement of the impaired one during bimanual actions (Lum et al., 2002). If no study has shown significantly superior results compared to unilateral training, active bimanual training may be an interesting approach to design simple robots that can train more severely impaired subjects (Hesse et al., 2003; Chang et al., 2007; Whitall et al., 2000). Further, practicing bilateral movements may result in a facilitation effect from the unimpaired arm to the impaired one, which may lead to faster and greater improvements (Stinear and Byblow, 2002; Winstein et al., 2003; Stewart et al., 2006).

Among robot-assisted studies with chronic stroke survivors, active movements generated by the subject against resistance from the robotic device seem to be the ideal solution for subjects with mild impairments. In their work, Fasoli et al. observed additional hand and wrist motor improvement during active-resisted arm movements with the MIT-MANUS, as compared to active-assisted movements. Active-resisted movements emphasized strength and greater distal muscle activation, in addition to joint coordination, which may offer substantial advantages to train functional tasks (Fasoli et al., 2004; Hogan et al., 2006). Though necessary for severely impaired subjects suffering from paresis e.g. subjects in the sub-acute phase, passive movements benefit less from the potential of robotic devices (Kahn et al., 2006), as no haptic effect is provided.

Therapies with CIMT, or drug injection together with physical training, have shown similar to superior improvements in motor function for chronic subjects (Sun et al., 2006; Leeman et al., 2008). However, these intensive and constraining techniques can only be applied to stroke survivors with limited physical impairment (Boake et al., 2007), i.e. capable of walking and with already partially restored hand function. Robot-assisted therapy with the *Haptic Knob* only requires minimal hand function to place the hand on the robot, and is available to a wider range of subjects, right or left handed, and with various level of physical impairment e.g. initial FMA score lower than 15, as demonstrated by this study.

Improvements in the FMA and MAS resulting from the therapy with the *Haptic Knob* are mainly observed in the components related to the upper arm, i.e. elbow and shoulder movements in and out of synergies, and interjoint coordination. These results may indicate a decrease in abnormal synergies in flexor muscles of the arm, thus improving the ability of subjects to perform and control movements, typically flexing and extending the elbow, supinating and pronating the forearm. These observations support the hypothesis that exercising distal parts of the arm may benefit the proximal parts (Buetefisch et al., 1995; Carey et al., 2002; Krebs et al., 2007; Takahashi et al., 2008). Distal arm training involves nerves and muscles that are connected to each segment of the upper limb, and will also result in proximal muscle activity of the arm. Indeed, while training with the *Haptic Knob* subjects worked hard with their entire arm to perform the required tasks, especially for the pronation/supination exercise, thus involving elbow and shoulder, typically to stabilize the arm.

Robot-assisted studies focusing on arm movement, and those training wrist and hand obtained similar improvement in FMA, as shown in Table 6.7. Nevertheless, in studies training shoulder and elbow only, improvement is mainly observed in the subportion of the FMA relative to the upper arm, while only minimal change is observed in the components relative to the hand. Such results may lead to an increase in arm function, however, without a similar increase in wrist and hand function, the benefits in subjects' ability to perform ADL may be limited. Robot-assisted studies training hand and wrist movements obtained increases in both subportions of the FMA.

In their study (Krebs et al., 2007), Krebs et al. compared two groups exercising arm planar movement with the MIT-MANUS, or wrist movements with a specially designed wrist module. Their results suggest that after 6 weeks of robot-assisted therapy both groups obtained similar increase in FMA scores. However, the group training wrist movements showed larger increases in the score related to the wrist and hand compared to the other group, suggesting a better repartition of the effects of training. Training distal segments of the arm may thus help improving arm fucntion in a more homogeneous way that may lead to larger improvement in ADL.

In our study, a similar trend can be observed, with significant improvements in the upper arm components of the FMA, but also at the level of the wrist and hand, especially in subjects with less severely impaired arm function. Dexterity and coordination for gripping objects is improved, along with a decrease in spasticity of upper limb flexor muscles. This indicates a greater ability to use and control the hand and wrist. These results and observations seem to support our approach of using end-effector based robots to provide therapy focused on distal segments of the arm. However, additional experiments with the *Haptic Knob* and our other devices investigating different experimental protocols are required to confirm this hypothesis.

It is likely that the severity of motor impairment is a key factor in rehabilitation outcomes and in the choice of a rehabilitation protocol. Larger increases in functional assessment scores during the therapy were observed in subjects with mild impairment (FMA >30), suggesting that subjects with some motor function of the arm and hand may benefit more from the functional hand therapy with the *Haptic Knob*. More severely impaired subjects may require longer or more intensive therapy to first strengthen the muscles, decrease spasticity and other impairments limiting their performance, and focus on the restoration of neuromotor pathways without introducing additional requirements for motor planning and perceptual processing during object interaction (Fasoli et al., 2005).

Nevertheless, every participant to the study improved arm and hand motor function as a result of the therapy with the *Haptic Knob*, which illustrates the flexibility of the exercise in accommodating various levels of impairment.

Finally, it is also interesting to note that the scores observed in the exercises with the *Haptic Knob* show similar improvements to the clinical assessments. Figure 6.10 compares the variation in the FMA with the variation of the mean scores of each exercise, S_1 and S_2 between the first and last sessions. This illustrates that a robotic device such as the *Haptic Knob* can be used as assessment tool to monitor stroke subjects' hand function.

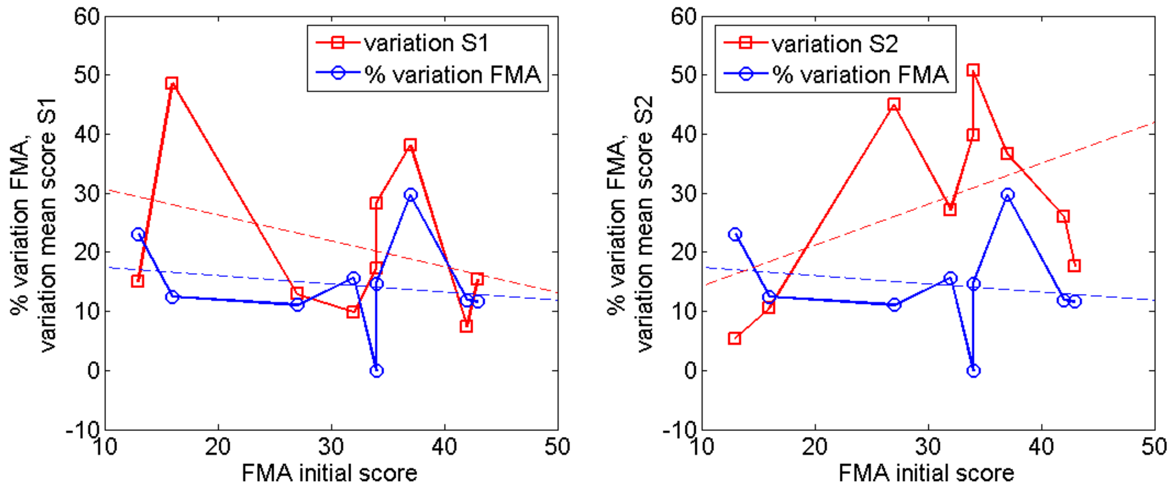

Figure 6.10: Variation of the mean score of the opening/closing exercise (left) and pronation/supination exercise (right), compared with the variation of the Fugl-Meyer scores during the 6 weeks robot-assisted therapy. Each point of the curves represents one of the stroke subjects, and dashed lines are linear fits.

Table 6.7: Results of robot-assisted studies for upper limb post-stroke rehabilitation (ranked by initial FMA score, n: number chronic stroke subjects involved in the study, y: years old, mps: months post-stroke, s/e: subportion of the FMA related to shoulder and elbow, range [0-42], w/h: subportion of the FMA related to the wrist and hand, range [0-24]).

study	objectives	protocol	stroke subjects	initial FMA	change
Hesse et al. 2008	Training of finger flexion/extension with the Finger Trainer (see Section 2.4)	4 weeks/20 sessions 15 minutes per session Passive movements with tactile stimulation during finger movement.	n=2 61.0 y 19.5 mps	8.0	+3.0 (38%)
Volpe et al. 2008	Training of shoulder and elbow during reaching movements with the MIT-MANUS robot.	6 weeks/18 sessions 1 hour per session Exercises composed of active assisted or active resisted movements	n=11 62.0 y 35.0 mps	15.3	+4.1 (27%) s/e: +2.9 w/h: +1.2
Krebs et al. 2007	Training of wrist movements (flex./ext., adb./add. and pron./sup.) using a 3DOF wrist module fixed to the MIT-MANUS.	6 weeks/18 sessions 1 hour per session Exercises composed of active-assisted or active-resisted movements	n=17 60.5 y 28.2 mps	17.4	+4.2 (24%) s/e: +2.2 w/h: +1.9
Krebs et al. 2007	Training of shoulder and elbow during reaching movements with the MIT-Manus robot.	6 weeks/18 sessions 1 hour per session Training composed of active-assisted or active-resisted movements	n=19 60.5 y 28.2 mps	17.4	+4.3 (25%) s/e: +3.8 w/h: +0.5
Nef et al. 2007	Training of shoulder and elbow during three dimensional arm movements with the ARMin robot.	8 weeks/24 sessions 1 hour per session Exercises with active and active assisted movements.	n=3 n.a. 14 to 40 mps	20.3	+3.4 (17%)

study	description	protocol	stroke subjects	initial FMA	change
Lum et al. 2002	Training of shoulder and elbow during reaching movements with a robot manipulator, the MIME. This robot can provide bimanual training where movement of the unimpaired limb is mirrored to the impaired limb.	8 weeks/24 sessions 1 hour per session Exercises start with passive and bimanual movements and progress to more challenging active and active-resisted movements.	n=13 63.2 y 30.2 mps	24.8	+4.7 (19%) s/e: +3.3 w/h: +1.4
Fasoli et al. 2004	Goal-directed planar reaching tasks with the MIT-MANUS robot to train shoulder and elbow.	6 weeks/18 sessions 1 hour per session Exercises composed of active-assisted or active-resisted movements.	n=42 57.4 y 28.7 mps	27.5	+3.4 (12%)
Fasoli et al. 2003	Goal-directed planar reaching tasks with the MIT-MANUS robot to train shoulder and elbow.	6 weeks/18 sessions 1 hour per session Active movements with resistance applied by the robot.	n=7 55.5 y 31.0 mps	30.3	+3.7 (12%)
Lambercy et al.	Training of grasping and pronation/supination with the *Haptic Knob*.	6 weeks/18 sessions 1 hour per session Exercises composed of active resisted movements.	n=9 59.4 y	30.9	+4.3 (14%) s/e: +3.1 w/h: +1.2
Takahashi et al. 2008	Training of grasping function using the HWARD robot.	3 weeks/15 sessions 1.5 hour per session Exercises composed of active assisted and active non-assisted movements.	n=15 63.0 y 34.8 mps	44.6	+7.6 (17%) s/e: +3.7 w/h: +4.0

Chapter 7

Conclusions

This chapter summarizes the different contributions presented in this thesis. Technical points that need to be considered in future for the design of robotic systems and experimental protocols are then analyzed, and solutions to complement and improve stroke rehabilitation are proposed.

7.1 Contributions

This thesis investigated robot-assisted rehabilitation of hand function after stroke. Its contributions consist in the development of simple robotic devices to train typical wrist and hand function corresponding to activities of daily living which stroke subjects desire to recover most, taking into consideration the biomechanical requirements of each subject and adapting to them. Functional rehabilitation systems with adaptable game-like virtual reality exercises enhancing subjects' motivation and participation were developed and tested on healthy and stroke subjects. Finally, robot-assisted therapy to train hand function using one of the robot, the *Haptic Knob*, was systematically tested by chronic stroke subjects in a clinical study performed at Tan Tock Seng Hospital (TTSH) in Singapore.

7.1.1 Robotic devices and the *Haptic Knob*

Traditional stroke rehabilitation has been examined in Chapter 2 as the starting point of this work. The therapy stroke survivors receive is often not sufficient for them to fully recover hand function, leaving them with various hand impairments which severely limit their independence and social integration. The analysis of actual stroke therapies shows that several new approaches have been investigated for improving rehabilitation, typically the integration of robotic devices for assessment and therapy. Existing robotic devices have been reviewed and discussed to define the most important aspects for the design of new efficient robots for hand rehabilitation.

The first part of this work consisted of the development of robotic devices to train typical hand and wrist functions after stroke: handwriting, typing, knob and object manipulation. Simple behavioral experiments with healthy and stroke subjects determined the biomechanical constraints for the design of safe, effective, compact and comfortable robotic devices described in Chapter 3.

To train the desired functional tasks and simplify the design, three robotic systems were developed to train specifically one part of the upper limb: arm, hand and fingers. One of the devices, the *Haptic Knob*, was conceived to train grasping in combination with wrist pronation/supination, two functions required to operate knobs, and in many other daily tasks. The development, implementation and evaluation of the *Haptic Knob* is the principal contribution of this work. This robot provides safe and smooth interaction with human movements, and is easily adaptable to the user as a function of his or her impairment level. The interface is easy to operate and portable, so that it can be used in decentralized rehabilitation centers or at home. Further, the possibility of recording position and force enables assessment of impairments and quantitative evaluation of hand and wrist function.

The constraints identified for the design of the devices, the catalogue of solutions proposed, the details of the implementation, and the evaluation approach used to test the *Haptic Knob* may be used for the development of other robotic devices for rehabilitation after stroke.

7.1.2 Rehabilitation exercises and protocols

The second part of this work consisted of the design of exercises for stroke rehabilitation, which was investigated in Chapter 4. To provide a good rehabilitation system, efficient exercises are required, which take advantage of the robot properties. Several approaches were investigated, and exercises requiring active participation of subjects against resistance from the robot, i.e. active-resisted exercises, have been selected. This strategy helps in the development of muscle strength, trains motor control and coordination of wrist, hand and fingers, and stimulates motor learning by actively performing actions and interacting with force fields.

The exercises can be adapted to provide subject specific therapy with challenging levels of difficulty adapted to their current impairment level. Motivation is essential for repeating movements over and over to produce effective stroke rehabilitation, and exercises should concentrate on enhancing subject's motivation to train and use the impaired limb. Our approach is to provide therapy composed of simple and challenging game-like exercises, using targeted feedback and taking advantage of the properties of robotic devices. Three interactive exercises were designed with the *Haptic Knob*, to train grasping movement, wrist pronation/supination, and the control of grasping force. Visual and proprioceptive cues were provided, which were tested with and well appreciated by healthy and post-stroke subjects. Most importantly psychological feedback, consisting of written encouragment on the GUI, helped subjects evaluate their performance and improve them.

7.1.3 Therapy with the ***Haptic Knob***

The third part of this work consisted of the evaluation of the *Haptic Knob* and the two other robotic devices as post-stroke rehabilitation tools. A pilot study, described in Chapter 5, was performed with 4 chronic stroke subjects training a combination of exercises with the three robots during 8 weeks (16 sessions). This study was one of the first to propose robot-assisted therapy at all levels of the upper limb, with specific exercises actively training arm, wrist and finger functions. As a result of the personalized therapy, each subject improved in the trained tasks, and a reduction of their hand impairments was observed. Subjects also reported functional improvements in activities of daily living.

To further investigate the effect of hand training, a larger clinical study described in Chapter 6 and involving 9 chronic stroke subjects, has been performed using the *Haptic Knob* only. Each subject received therapy sessions focusing on grasping and wrist pronation/supination movements during 6 weeks (18 sessions). Results of the study showed a significant decrease in arm impairment, a decrease in arm and hand spasticity, and an improvement in hand functional activities. These improvements were maintained 6 weeks after completion of the therapy, suggesting long term motor improvement of the hand function. These results and positive comments from subjects confirm the potential of this robot therapy for rehabilitation of hand and wrist function after stroke, and provide data to analyze the effect of robot-assisted rehabilitation of chronic stroke subjects.

In addition to providing therapy, the *Haptic Knob* can be a useful tool to assess a subject's motor function. The position and force sensors of the robot can efficiently record kinematics and dynamics of the hand during each exercise. Parameters such as motion smoothness or precision can be extracted using the algorithms proposed in this thesis to quantitatively characterize subject's performance, track improvement, and measure the functional activity trained by the robot.

With this project, 22 stroke subjects performed movements with the *Haptic Knob*, in Canada and in Singapore. In total, more than 250 hours of active therapy with the robot have been performed, which corresponds to about 25,000 movements. The participants were satisfied with the proposed therapy, no pain or complications were reported, and subjects found the interactions with the robot challenging and motivating. Subjects reported improvements in their hand function, and seemingly regained motivation to fight their impairment and involve their impaired hand in daily activities. This may lead to further improvements of hand function, and importantly improve their quality of life.

7.2 Outlook

Robot-assisted rehabilitation complementing traditional therapies, as was illustrated in this work and other studies using robotic devices, have shown some promise in rehabilitation. However, robot-assisted rehabilitation requires further analysis and has potential for improvement. The following points present possible directions to consider in future developments.

Therapy protocols

The main advantage of robots over traditional therapies may be the larger number of movements that can be trained during a single therapy session (Kwakkel et al., 2008). In a recent study, Volpe et al. showed that with equal intensity, the outcome of traditional rehabilitation was similar to robot-assisted rehabilitation (Volpe et al., 2008). However, increased traditional therapy requires substantial human resources precluding large scale use.

Nevertheless, robot-assisted rehabilitation protocols should be refined to fully benefit from the advantages of robotic systems. Typically, principles of motor learning may be systematically used in rehabilitation, with exercises focusing more on active participation, with intensive repetition of movements initiated and controlled by the subject, involving interaction with different force fields and feedback (Krakauer, 2006).

Further, more studies should investigate the effect of distal versus proximal therapy for hand and arm rehabilitation. Indeed, as suggested by this work, the use of end-effector robotic devices focusing on distal training may lead to additional improvements by enhancing joint coordination and proper muscle activation (Fasoli et al., 2005; Krebs et al., 2007). The *Haptic Knob* used in combination with the other robots presented in this work could be used to further investigate this hypothesis.

Integration of new technologies for stroke rehabilitation

The application of new technological tools to complement and improve robot-assisted rehabilitation should be investigated. The use of a brain computer interface (BCI) to control a robotic orthosis or robotic devices is a possible approach. Recent advances in analysis of brain signals, training patients to control these signals, and improved computing capabilities have enabled people with severe motor disabilities to use brain signals to bypass their impaired neuromuscular system and directly perform movements and control objects in their environment (Daly and Wolpaw, 2008).

In a similar way, electromyography (EMG) could be used to detect voluntary muscle activation, and assist the subject to perform movements by controlling a robotic device (Di Pietro et al., 2005; Andreasen et al., 2005).

Functional Electrical Stimulation (FES) could be added to a robotic system to stimulate arm or hand muscles in a way to extend a subject's ability to perform tasks assisted by a robot (Hughes et al., 2006).

Transcranial magnetic stimulation (TMS) is currently used to assess cortical reorganization, but could be used to directly help in performing movements by stimulating the motor cortex (Brown, 2006; Young and Kong, 2007).

Robotic devices as assessment tools

In addition to facilitating therapy, robotic devices have a high potential for assessment. Parameters measured during training could be used to quantitatively evaluate progress during the therapy, and consequently adapt the intensity and difficulty of therapy.

Future rehabilitation tools could possibly be used for standard clinical assessment to evaluate stroke subjects' impairments, e.g. spasticity, muscle strength, or range of motion, and quantitatively determine the most apropriate therapy protocols to be applied. Further, robots may be used to assess functional activity of subjects, which is often not well addressed by traditional clinical assessments. Robots would give therapists objective and quantitative measures of subjects' impairments that may help in performing rehabilitation in a more scientific way.

Towards home rehabilitation

Rehabilitation devices are useful if they are used by subjects. One of the main challenges in the development of rehabilitation tools is to provide solutions that can be integrated in hospitals, rehabilitation centers, and intensely used in therapy sessions. A main objective is to propose devices that can be used at home in the context of the subjects' daily activities. This may further increase intensity and motivation to train and lead to additional improvement of the motor function. To achieve such goal, robotic devices should be safe, easy to use, requiring no interaction from therapist or engineer, adaptable to a wide range of subjects, and low-cost for subjects to buy or rent. Therapy with such device could then be remotely monitored by a therapist via an Internet connection to track subject's progression and adapt the training parameters (Reinkensmeyer et al., 2002; Burdea, 2003; Huijgen et al., 2008).

Our devices and in particular the *Haptic Knob* are a step in this direction. Minimal set up is required to use the robot; the device is compact, can easily be transported and could be installed on a new personal computer in a few minutes. After few sessions of therapy, several subjects who trained with the robot were able to position their hand by themselves and adjust their finger position during therapy.

Finally, although results of studies on robot-assisted rehabilitation after stroke are positive and promising, the number of patients treated so far, and the amout of data available remains small compared to well established traditional therapies. In the future, researchers should focus on performing more clinical studies to gather more evidences on the effectiveness of robot-assisted rehabilitation, favor the integration of robotic tools into rehabilitation centers and at home, and propose therapy to a larger number of stroke survivors.

Appendix A

Results of the clinical study for the opening/closing exercise and the pronation/supination exercise

Table A.1: Results of the opening/closing exercise for each participant of the clinical study for the first (S1) and last (S18) sessions.

		ϵ_p	n_0	S_1	n_f	F_{ot}	F_{of}	F_{ct}	F_{cf}	F_{rt}	F_{rf}	ϵ_f
A1	S1	4.04 ±3.02	7.01 ±0.49	62.6 ± 28.9	9	14.5 ± 3.0	12.7 ± 2.8	12.4 ±1.4	9.8 ±1.3	19.8 ±3.2	16.9±2.6	3.17±1.44
	S18	3.28 ±1.91	6.37 ± 0.73	77.7 ± 9.5	2	16.2 ± 3.3	14.0 ±2.9	9.2 ±1.2	7.7 ±1.8	20.6 ±4.1	13.9 ±2.6	2.43±1.81
	%	-18.8	-9.1	+24.1	-77.8	+11.7	+10.2	-25.8	-21.4	+4.0	-17.8	-23.3
	p	0.13	<0.001	0.001		0.20	0.34	<0.001	<0.001	0.28	<0.001	0.006
A2	S1	4.77 ±3.15	6.39 ±0.66	57.4 ±35.0	16	11.1 ±3.1	9.8±2.7	12.4 ±2.6	10.8±3.8	14.7±4.3	15.1±2.9	3.72±4.01
	S18	1.79 ±0.58	5.91 ±0.61	85.7 ±4.5	0	8.9±2.4	9.2±2.4	9.9±1.8	10.5±1.8	16.0±3.9	14.1±2.9	2.91±1.67
	%	-62.4	-7.5	+49.3	-100	-19.8	-6.1	-20.1	-2.8	+8.8	-6.6	-23.0
	p	<0.001	<0.001	<0.001		0.001	0.53	<0.001	0.67	0.11	0.11	0.25
A3	S1	3.61±3.35	6.23±0.49	69.4±31.0	12	9.5±4.3	14.5±2.9	10.7±3.7	15.2±3.0	15.5±5.7	18.6±4.0	5.78±3.63
	S18	2.59±1.05	5.63±0.60	79.3±7.8	0	4.6±1.6	12.5±3.3	6.3±1.1	14.5±1.9	9.8±2.7	17.5±3.9	8.25±1.98
	%	-28.2	-9.6	+14.3	-100	-51.6	-13.8	-41.1	-4.6	-36.8	-5.9	+42.7
	p	0.04	<0.001	0.03		<0.001	0.003	<0.001	0.20	<0.001	0.20	<0.001
A4	S1	1.69±1.01	5.20±0.66	86.3±5.2	0	2.2±1.4	3.7±1.4	9.6±1.3	12.3±1.1	6.7±3.4	8.7±2.5	2.83±1.67
	S18	1.07±0.39	5.51±0.64	91.7±3.2	0	3.0±0.8	3.3±0.7	10.6±0.8	10.4±0.8	6.8±2.1	7.2±1.6	0.82±0.46
	%	-36.7	+6.0	+6.3	0	+36.4	-10.8	+10.4	-15.4	+1.5	-17.2	-71.0
	p	<0.001	0.02	<0.001		<0.001	0.03	<0.001	<0.001	0.87	<0.001	<0.001
A5	S1	3.37±3.28	5.68±0.65	73.6±27.6	2	3.2±1.8	14.5±3.0	1.7±1.44	15.4±3.0	5.4±3.1	18.2±4.0	13.95±3.57
	S18	1.13±0.34	5.01±0.62	90.9±2.8	0	4.1±4.2	9.6±2.5	4.6±5.6	10.3±2.1	8.8±5.1	14.0±3.0	7.44±4.10
	%	-66.5	-11.8	+23.5	-100	+28.1	-33.8	+170.5	-33.1	+63.0	-23.1	-46.7
	p	<0.001	0.002	<0.001		0.17	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
A6	S1	7.15±2.39	6.68±0.35	19.1±26.2	44	4.9±2.7	6.9±1.7	8.9±2.0	9.6±1.1	8.4±3.5	9.0±2.1	2.41±0.92
	S18	3.98±1.87	5.64±0.49	67.7±16.4	2	2.7±1.3	5.8±2.0	8.8±1.7	10.4±1.5	5.6±2.1	8.1±2.2	1.93±1.06
	%	-44.3	-15.6	+254.5	-95.5	-44.9	-15.9	-1.1	+8.3	-33.3	-10.0	-19.9
	p	<0.001	<0.001	<0.001		<0.001	0.003	0.82	0.003	<0.001	0.03	0.015
A7	S1	2.13±1.13	5.81±0.70	83.3±8.9	0	6.5±2.2	10.4±1.6	11.1±1.2	14.0±0.9	12.1±2.6	15.0±2.4	2.84±1.59
	S18	1.14±0.41	6.10±0.54	90.8±3.3	0	7.1±2.1	14.1±2.3	10.9±1.9	16.5±1.5	12.4±2.6	16.7±1.8	5.57±2.97
	%	-46.5	+4.8	+9.0	0	+9.2	+35.6	-1.8	+17.9	+2.5	+11.3	+96.1
	p	<0.001	0.02	<0.001		0.21	<0.001	0.51	<0.001	0.56	<0.001	<0.001
A8	S1	3.10±1.63	5.93±0.69	75.1±14.6	1	1.1±1.1	3.1±1.2	5.2±2.1	7.6±2.1	1.7±1.6	3.8±1.5	2.35±1.41
	S18	1.45±1.51	4.91±0.67	88.2±12.3	0	4.6±1.4	7.3±1.8	9.3±0.8	13.5±0.9	8.7±2.8	11.5±3.5	4.26±0.86
	%	-46.5	+4.8	+9.0	0	+318.2	+135.5	+78.8	+77.6	+411.8	+202.6	+81.2
	p	<0.001	0.02	<0.001		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
A9	S1	7.66±2.75	6.32±0.55	43.8±26.3	21	1.2±0.9	3.6±1.2	2.1±1.4	9.8±3.9	1.9±1.3	4.6±1.1	8.07±3.78
	S18	2.27±0.95	6.32±0.67	81.9±7.6	0	4.8±1.5	7.1±1.6	6.8±1.5	14.3±2.8	6.9±2.4	8.0±1.8	7.52±2.81
	%	-70.3	-0.0	+87.0	-100	+300	+97.2	+223.8	+45.9	+263.2	+73.9	-6.8
	p	<0.001	0.99	<0.001		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.72

Table A.2: Results of the pronation/supination exercise for the first (S1) and last (S18) sessions.

		n_f	n_r	t_m	t_T	n_0	n_c	S_2
A1	S1	38	30	11.07±5.11	11.25±5.20	7.19±1.48	4.70±3.96	17.1±32.1
	S18	34	26	10.41±5.20	9.94±6.00	6.34±0.99	1.29±0.46	22.5±34.4
	%	-10.5	-13.3	-5.9	-11.6	-11.8	-72.5	+31.6
	p			<0.001	<0.001	0.03	<0.001	0.41
A2	S1	36	29	10.23±5.76	10.88±5.53	6.43±0.94	2.81±2.29	23.4±37.4
	S18	4	0	2.27±1.09	4.28 ±3.05	6.68±1.12	5.26±5.23	74.2±28.0
	%	-88.9	-100	-77.8	-60.7	+3.9	+87.2	+217.1
	p			<0.001	<0.001	0.37	0.04	<0.001
A3	S1	43	39	12.92±4.26	13.09±3.92	6.64±0.76	6.09±4.85	7.4±20.2
	S18	20	10	7.09±4.55	6.89±4.78	6.68±0.94	4.25±3.51	34.6±31.8
	%	-53.5	-74.4	-45.1	-47.4	+0.6	-30.2	+367.5
	p			<0.001	<0.001	0.89	0.16	<0.001
A4	S1	2	0	3.71±1.90	4.11±2.53	5.80±0.73	3.30±2.41	62.8±24.1
	S18	0	0	3.29±1.19	2.34±0.83	5.91±0.79	1.64±1.24	84.5±14.0
	%	-100	-	-11.3	-43.1	+1.9	-50.3	+34.5
	p			0.19	<0.001	0.47	<0.001	<0.001
A5	S1	30	6	5.76±4.20	9.13±4.09	5.80±0.93	6.84±3.95	20.4±31.0
	S18	6	0	3.55±1.45	4.78±3.42	5.81±0.82	3.82±3.05	60.2±28.8
	%	-80.0	-100	-38.3	-47.6	+0.2	-44.2	+195.1
	p			<0.001	<0.001	0.98	<0.001	<0.001
A6	S1	47	25	10.88±4.72	11.35±4.44	5.66±0.99	5.04±2.95	3.4±14.5
	S18	37	7	5.14±4.47	10.51±3.57	5.72±1.11	11.16±7.49	13.9±25.8
	%	-21.3	-72	-52.8	-7.4	+1.1	+121.4	+308.8
	p			<0.001	0.06	0.84	<0.001	0.01
A7	S1	3	0	3.62±1.62	3.52±2.43	6.25±0.68	2.88±2.59	70.3±28.2
	S18	0	0	1.94±0.72	2.18±0.58	5.61±0.98	1.28±0.90	96.3±7.9
	%	-100	0	-46.4	-38.1	-10.2	-55.6	+37.0
	p			<0.001	<0.001	<0.001	<0.001	<0.001
A8	S1	7	0	4.19±1.88	5.39±3.04	5.58±0.87	5.50±3.88	47.4±27.4
	S18	0	0	2.23±0.82	2.42±0.97	5.98±0.72	1.64±1.31	92.4±12.7
	%	-100	0	-46.8	-55.1	+7.2	-70.2	+94.9
	p			<0.001	<0.001	0.01	<0.001	<0.001
A9	S1	4	0	6.45±1.67	3.14±1.64	6.31±0.78	2.38±1.89	44.2±18.9
	S18	0	0	2.60±0.92	2.24±0.53	5.01±1.11	1.60±1.16	90.9±10.7
	%	-100	0	-59.7	-28.7	-20.6	-32.8	+105.7
	p			<0.001	<0.001	<0.001	0.01	<0.001

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